

**NASA TECHNICAL MEMORANDUM 101506**

**MATERIALS DIVISION RESEARCH AND TECHNOLOGY  
ACCOMPLISHMENTS FOR FY 87  
AND PLANS FOR FY 88**

**Kay L. Brinkley**

**(NASA-TM-101506) MATERIALS DIVISION  
RESEARCH AND TECHNOLOGY ACCOMPLISHMENTS FOR  
FY 87 AND PLANS FOR FY 88 (NASA) 134 p**

**CSCL 07A**

**N89-18528**

**G3/23 0188207**

**Unclass**

**December 1988**



**National Aeronautics and  
Space Administration**

**Langley Research Center  
Hampton, Virginia 23665-5225**

**MATERIALS DIVISION  
RESEARCH AND TECHNOLOGY ACCOMPLISHMENTS FOR FY 87  
AND PLANS FOR FY 88**

**SUMMARY**

The research program of the Materials Division is presented as FY 87 accomplishments and FY 88 plans. The accomplishments for each Branch are highlighted and plans are outlined. Publications of the Division are included by Branch. This material will be useful in program coordination with other government organizations, universities, and industry in areas of mutual interest.

**ORGANIZATION**

The Langley Research Center is organized by directorates as shown in figure 1. Each directorate is organized into divisions and offices. The Materials Division of the Structures Directorate consists of four branches as shown in figure 2. This figure also shows the technical areas addressed by each Branch. The Division consists of 69 NASA civil servants and 7 members of the Army Aerostructures Directorate, USAARTA, Army Aviation Systems Command, located at the Langley Research Center. In addition, about 38 non-personal support contractors work at the Center to add major support to the in-house research program.

**FUNCTIONAL STATEMENT**

The Materials Division initiates, organizes, and conducts experimental and analytical research on structural materials and their application to aircraft and spacecraft structural systems (figure 3). More specifically the Division:

- Conducts fundamental and applied research studies to develop novel polymeric, metallic, and ceramic materials for advanced structural applications.
- Establishes materials processing and fabrication technology for structural components.
- Demonstrates the application and benefits of advanced materials to specific flight vehicle structures.
- Defines, evaluates, and conducts research on thermal protection materials requirements for high-speed aircraft and space transportation systems.
- Studies the fatigue and fracture behavior of materials to establish practical methods for insuring the structural integrity of aircraft and space structures.
- Characterizes the behavior of structural materials in extreme service environments using test facilities and laboratories for simulation of the flight environment.
- Originates and develops requirements for new facilities and research techniques.
- Operates the fatigue and fracture, structural materials, polymer, metallurgical, and environmental effects laboratories.

The long range research thrusts of the Materials Division are shown in figure 4.

## **FACILITIES**

The Materials Division has four major facilities to support its research program.

The Structures and Materials Laboratory houses various environmental effects labs and the metallurgical and metals processing labs. In the environmental effects labs, research is conducted to characterize and enhance the performance of structural materials operating in extreme service environments. Test techniques, instrumentation, and measurement techniques are developed to simulate environmental conditions required to evaluate high-temperature structural materials. The interaction of the space environment on properties of advanced composites, polymer films, and coatings for space systems is studied. Radiation and monoatomic oxygen damage in polymeric materials is studied and chemical formulations for enhanced long-term durability in space are identified.

Fundamental and applied research on advanced metallic and metal-matrix materials is conducted in the metallurgical and metals processing labs. Innovative processing methods for new alloy synthesis and development and fabrication of metallic structural components for future aircraft and space vehicles, including high-temperature applications, are explored. Metallic components are analyzed and tested to demonstrate improvements in advanced metallic alloys and their fabrication processes.

The Fatigue and Fracture Laboratory is used to conduct research on the structural integrity of metals and composites for aircraft structures. Tests are conducted to measure the effect of loads on materials under simulated flight conditions. Materials and methods of strength and life prediction for airframes are assessed to develop ways to improve the structural reliability of aircraft.

Fundamental and applied research using advanced polymer synthesis, composites and adhesives processing science, and advanced characterization methodology to develop improved materials concepts for efficient aerospace structures are conducted in the Composites Processing Laboratory. Novel polymeric materials are synthesized for applications such as matrices for fiber-reinforced composites, adhesives for bonding lightweight composite and metal structures, and high-performance films for spacecraft. Innovative processing methods for fabricating composite components for aircraft and spacecraft structures are developed.

Radiation testing of spacecraft materials is conducted in the Space Environmental Effects Laboratory. Spacecraft materials tested include polymeric and metal matrix composites, polymeric films, thermal control coatings, adhesives, solar cells, and laser mirrors.

In addition, the Materials Division is currently constructing a Carbon-Carbon Research Laboratory that is expected to be completed in July 1988. The Materials Division has expanded its research capability in carbon-carbon materials and this lab will house the processing equipment needed for fabricating carbon-carbon materials and for applying oxidation-protective coatings.

## **FY 87 ACCOMPLISHMENTS**

### **Polymeric Materials Branch**

The Polymeric Materials Branch (figure 5) conducts fundamental and applied research studies combining the disciplines of advanced polymer synthesis, composites and adhesives processing science, and advanced characterization methodology to develop improved materials concepts for efficient aerospace structures. These research and development activities are aimed at achieving maximum structural exploitation of advanced composites and adhesives through development of balanced mechanical/physical properties with good processability. The five year plan for this research is shown in figure 6.

The FY 87 accomplishments of the Polymeric Materials Branch are listed below and are highlighted in figures 7 through 11.

#### **High Performance Polymer Concepts**

- Polymer Technology Transfer
- Preparation of Amide-Imide Polymers

#### **Composite Matrices**

- Crystallization in Thermoplastic Resins - LARC-TPI

#### **Composite Processing and Adhesive Bonding**

- LARC-TPI Composites Via New Slurry Process
- The Effect of Diamic Acid Additives on the Processability of Polyimides

### **Fatigue and Fracture Branch**

The Fatigue and Fracture Branch (figure 12) performs research on the integrity of materials for load-bearing structures of metals and composites. This research includes fatigue, fracture mechanics, and structural reliability. Equations and analytical methods are formulated to predict fatigue life and residual strength of damaged and undamaged materials. Design, construction, operation, and inspection methods applied to airframes are assessed to develop ways to improve the overall structural reliability of aircraft and spacecraft. The five year plan of the Branch is shown in figure 13.



The FY 87 accomplishments of the Fatigue and Fracture Branch are listed below and are highlighted in figures 14 through 25.

#### **Metals and Metal Matrix Composites**

- Fatigue Life of Material With a Machining Scratch
- Three-Dimensional Analysis of Fatigue Crack Closure
- Fiber-Matrix Separation in Silicon Carbide/Titanium Matrix Composites

#### **Composites**

- Delamination Fatigue Behavior of Composite Materials
- Matrix Yielding at a Delamination Front
- Interlaminar Shear Fatigue Thresholds For Composite Materials

#### **Computational Methodology**

- Calculation of Strain-Energy Release Rate Distribution Using Plate Analysis
- Boundary Force Method For Analyzing Cracked Laminates
- Strain Energy Release Rates for Edge-Delaminated Composite Laminates
- Fiber-Resin Micromechanics Analysis of Delamination
- Finite-Element Analysis of End Notched Flexure (ENF) Specimen
- Finite-Element-Alternating Method for Crack Analyses

### **Applied Materials Branch**

The Applied Materials Branch (figure 26) conducts research to characterize and enhance the performance of structural materials operating in extreme service environments. The Branch identifies mechanisms of environmental degradation and failure in structural materials, provides quantitative understanding of degradation mechanisms and evolves models to predict the rate or extent of degradation for various advanced structural materials. Theoretical and experimental studies which relate to the environmental performance of high-temperature materials for thermal protection systems and hot structures of advanced space transportation systems and hypersonic vehicles are conducted. The interaction of the space environment on properties of advanced composites, polymer films, and coatings of interest for space systems is studied. The five year research plan for the Branch is shown in figure 27.

The FY 87 accomplishments of the Applied Materials Branch are listed below and are highlighted in figures 28 through 34.

#### **Space Materials**

- Development of Protective Coatings for Composite Tubes
- A Comparison of the Effects of Simulated Low-Earth and Geosynchronous Orbit Exposure on Composite Materials
- Thermally Induced Twist in Composite Tubes

### **Composite Materials for Rotorcraft and Aircraft Structures**

- Thermally Stable Graphite-Reinforced Aluminum Alloys
- A Method of Predicting the Energy-Absorption Capability of Composite Subfloor Beams
- Using Fundamental Spectroscopic Data to Explain Changes in Applied Properties of Irradiated Polymers
- Innovative Fabrication of Composite Structures

### **Metallic Materials Branch**

The Metallic Materials Branch (figure 35) conducts fundamental and applied research studies on advanced metallic and metal-matrix materials. The Branch performs research on advanced high-strength structural alloys and composites to achieve improved mechanical properties through understanding and control of microstructural features. A basic understanding of joining and forming processes for fabricating structural components from advanced metallic materials is developed and innovative processing methods for new alloy synthesis and development and fabrication of metallic structural components for future aircraft and space vehicles is explored. The five year research plan for the Branch is shown in figure 36.

The FY 87 accomplishments for the Metallic Materials Branch are listed below and are highlighted in figures 37 through 42.

#### **Advanced Light Alloy and MMC Development**

- B<sub>4</sub>C Particulates Show Promise to Improve Properties in Aluminum Matrix Composites
- Material Property Verification of LaRC Processed PM Aluminum Alloys
- Improved Aging Characteristics by Minor Alloying Additions in Al-Li Alloys

#### **Innovative Metals Processing**

- Alleviation of Cavitation in Superplastically Formed 7475 Aluminum Alloy Using Post-Forming Pressure

#### **High Temperature Thin Gage Metals and MMC for Airframes**

- Emittance/Catalysis Coatings Improve Performance of Titanium-Aluminides
- Liquid Interface Diffusion Bonding of Titanium Aluminides Shows Promise for Elevated Temperature Applications to 1700°F

## **PUBLICATIONS AND PRESENTATIONS**

The FY 87 accomplishments of the Materials Division are highlighted by a number of publications and presentations. These are listed by organization and are identified by the categories of formal NASA reports, quick-release technical memorandums, contractor reports, journal articles and other publications, meeting presentations, technical talks, tech briefs, and patents.

### **DIVISION OFFICE**

#### **Contractor Reports**

1. Jackson, A. C.; Balena, F. J.; LaBarge, W. L.; Pei, G.; Pitman, W. A.; and Wittlin, G.: Transport Composite Fuselage Technology - Impact Dynamics and Acoustic Transmission. (NAS1-17698 Lockheed-California Company) NASA CR-4035, December 1986.

#### **Journal Articles and Other Publications**

2. St. Clair, A. K.; St. Clair, T. L.; and Slem, W. S.: Optically Transparent/Colorless Polyimides in Recent Advances in Polyimides Science and Technology, W. D. Weber and M. R. Gupta, eds., 1987, p. 16-36.

#### **Meeting Presentations**

3. Swann, R. T.; Stroud, C. W.; and Ohlhorst, C. W.: Predicting In-Flight Material Performance From Ground-Based Test Data. Presented at the NASA Workshop on Oxidation-Resistant Carbon-Carbon for Hypersonic Vehicle Applications, September 15-16, 1987, Hampton, Virginia. NASA CP pending.
4. Tenney, D. R.; and Slem, W. S.: Radiation Durability of Polymeric Spacecraft Materials. Presented at the American Chemical Society and Royal Australian Chemistry Institute Workshop on Radiation Effects on Polymeric Materials, August 16-19, 1987, Queensland, Australia. Proceedings pending.

#### **Technical Talks**

5. St. Clair, A. K.: Aerospace Applications for High Temperature Polyimides. Presented at the State University of New York Short Course on High Temperature Polymers: Synthesis, Properties and Applications, January 19-22, 1987, Tokyo, Japan.

6. St. Clair, A. K.: Aerospace Applications for High Temperature Polyimides. Presented at the State University of New York Short Course on High Temperature Polymers: Synthesis, Properties and Applications, May 7-9, 1987, New Paltz, New York.
7. St. Clair, A. K.: Soluble and Colorless Polyimides. Presented at the State University of New York Short Course on High Temperature Polymers: Synthesis, Properties and Applications, May 7-9, 1987, New Paltz, New York.
8. St. Clair, A. K.: Soluble and Colorless Polyimides. Presented at the State University of New York Short Course on High Temperature Polymers: Synthesis, Properties and Applications, January 19-22, 1987, Tokyo, Japan.
9. St. Clair, A. K.; and St. Clair, T. L.: Soluble and Colorless Polyimides. Presented at the Meeting of the Society of Polymer Science, Japan, January 22, 1987, Tokyo, Japan.
10. Tenney, D. R.: Composite Materials for Aerospace Structures. Presented at the Materials Research Society Annual Spring Meeting, April 21-24, 1987, Anaheim, California.
11. Tenney, D. R.: Composite Program: NASA Langley Research Center. Presented at the VPI&SU, Virginia Department of Economic Development, et al., Composites in Virginia Workshop, September 28-29, 1987, Blacksburg, Virginia.

#### **Tech Briefs**

12. St. Clair, A. K.; and St. Clair, T. L.: Soluble Aromatic Polyimides for Film Coating Applications. NASA Tech Brief LAR-13700.
13. St. Clair, A. K.; St. Clair, T. L.; Winfree, W. P.; and Emerson, B. R., Jr.: Method for Preparing Low Dielectric Polyimides. NASA Tech Brief LAR-13769.

### **POLYMERIC MATERIALS BRANCH**

#### **Quick-Release Technical Memorandums**

14. Johnston, N. J.; and Hergenrother, P. M.: High Performance Thermoplastics: A Review of Neat Resin and Composite Properties. NASA TM-89104, February 1987.
15. Progar, D. J.: Evaluation of Ti-6Al-4V Surface Treatments for Use With a Polyphenylquinoxaline Adhesive. NASA TM-89045, October 1986.

16. Progar, D. J.; and Pike, R. A.: Adhesive Evaluation of Water-Soluble LARC-TPI. NASA TM-89152, June 1987.
17. St. Clair, T. L.; and Progar, D. J.: Adhesive Evaluation of New Polyimides. NASA TM-89140, April 1987.

### **Contractor Reports**

18. Bascom, W. D.: Interfacial Adhesion of Carbon Fibers. (NAS1-17918 Hercules, Inc.) NASA CR-178306, August 1987.
19. Bascom, W. D.; and Drzal, L. T.: The Surface Properties of Carbon Fibers and Their Adhesion to Organic Polymers. (NAS1-17918 Hercules, Inc.) NASA CR-4084, July 1987.

### **Journal Articles and Other Publications**

20. Bass, R. G.; Cooper, E.; Hergenrother, P. M.; and Connell, J. W.: Poly(enonsulfides) From the Addition of Aromatic Dithiols to Aromatic Dipropynones. Journal of Polymer Science, Part A: Polymer Chemistry, Volume 25, 1987, p. 2395-2407.
21. Burks, H. D.; Hou, T-H.; and St. Clair, T. L.: Characterization of Crystalline LARC-TPI Powder. SAMPE Quarterly, Volume 18, No. 1, October 1986, p. 1-8.
22. Burks, H. D.; and St. Clair, T. L.: Siloxane-Modified Polyethersulfideimide. Journal of Applied Polymer Science, Volume 34, 1987, p. 351-357.
23. Burks, H. D.; St. Clair, T. L.; and Progar, D. J.: Synthesis and Characterization of Copolyimides With Varying Flexibilizing Groups in Recent Advances in Polyimide Science and Technology, W. D. Weber and M. R. Gupta, eds., 1987, p. 150-163.
24. Connell, J. W.; Bass, R. G.; Sinsky, M. S.; Waldbauer, R. O.; and Hergenrother, P. M.: Polypyrazoles From Aromatic Dipropynones and Aromatic Dihydrazines. Journal of Polymer Science, Part A: Polymer Chemistry, Volume 25, 1987, p. 2531-2542.
25. Egli, A. H.; and St. Clair, T. L.: Enhancement of Molecular Weight Build Up in Polyimides Using Ether Solvents in Recent Advances in Polyimide Science and Technology, W. D. Weber and M. R. Gupta, eds., 1987, p. 57-66.

26. Ezzell, S. A.; St. Clair, A. K.; and Hinkley, J. A.: Synthesis and Characterization of Elastomer-Modified Polyimide Films. Polymer, Volume 28, September 1987, p. 1779-1786.
27. Filbey, J. A.; Wightman, J. P.; and Progar, D. J.: Sodium Hydroxide Anodization of Ti-6Al-4V Adherends. The Journal of Adhesion, Volume 20, No. 4, 1987, p. 283-291.
28. Harris, F. W.; Beltz, M. W.; and Hergenrother, P. M.: A New Readily Processable Polyimide. SAMPE Journal, Volume 23, No. 1, January/February 1987, p. 6-9.
29. Hergenrother, P. M.: Heat-Resistant Polymers. Encyclopedia of Polymer Science and Engineering, Volume 7, Second Edition, 1987, p. 639-665.
30. Hergenrother, P. M.: Recent Advances in High Temperature Polymers. Polymer Journal, Volume 19, 1987, p. 73-83.
31. Hergenrother, P. M.; Wakelyn, N. T.; and Havens, S. J.: Polyimides Containing Carbonyl and Ether Connecting Groups. Journal of Polymer Science, Part A: Polymer Chemistry, Volume 25, 1987, p. 1093-1103.
32. Hinkley, J. A.: Small Compact Tension Specimens for Polymer Toughness Screening. Journal of Applied Polymer Science, Volume 32, No. 6, November 5, 1986, p. 5653-5655.
33. Hou, T-H.; Bai, J-M.; and St. Clair, T. L.: A DSC Study on Crystalline LARC-TPI Powder - A New Version With Higher Initial Molecular Weight. SAMPE Quarterly, Volume 18, No. 4, July 1987, p. 20-24.
34. Johnston, N. J.; and St. Clair, T. L.: Thermoplastic Matrix Composites: LARC-TPI, Polyimidesulfone and Their Blends. SAMPE Journal, Volume 23, No. 1, January/February, p. 12-20.
35. Maudgal, S.; and St. Clair, T. L.: Siloxane Containing Polyimides With Improved Processability in Recent Advances in Polyimide Science and Technology, W. D. Weber and M. R. Gupta, eds., 1987, p. 37-56.
36. Progar, D. J.: Evaluation of Polyimide Films as Adhesives. Journal of Adhesion Science and Technology, Volume 1, No. 1, 1987, p. 53-68.
37. Progar, D. J.: Evaluation of Ti-6Al-4V Surface Treatments for Use With a Polyphenylquinoxaline Adhesive. Journal of Adhesion Science and Technology, Volume 1, No. 2, 1987, p. 135-144.

38. Progar, D. J.; and St. Clair, T. L.: A Thermoplastic Copolyimide in Recent Advances in Polyimide Science and Technology, W. D. Weber and M. R. Gupta, eds., 1987, p. 139-149.
39. Progar, D. J.; and St. Clair, T. L.: Flexibilized Copolyimide Adhesives. The Journal of Adhesion, Volume 21, 1987, p. 35-57.
40. St. Clair, T. L.: Matrix Resin Development at NASA Langley Research Center in High Temperature Polymer Matrix Composites, Tito T. Serafini, ed., 1987, p. 35-53.
41. Stoakley, D. M.; Shilady, D. D.; Vallarino, L. M.; Gootee, W. A.; and Smailes, D. L.: Selected Spectroscopic and Magnetic Properties of Lanthanide Complexes in Polyimide XU-218 in Recent Advances in Polyimide Science and Technology, W. D. Weber and M. R. Gupta, eds., 1987, p. 417-427.
42. Stoakley, D. M.; and St. Clair, A. K.: Lanthanide-Containing Polyimides in Recent Advances in Polyimides Science and Technology, W. D. Weber and M. R. Gupta, eds., 1987, p. 471-479.

#### **Meeting Presentations**

43. Dominek, A.; Shamansky, H.; Burkholder, R.; Wood, R.; Hodges, W. T.: A Method of Evaluating Conductive Coatings for RCS Models. Presented at the 9th Annual Meeting and Symposium of the Antenna Measurements Techniques Association, September 2 - October 1, 1987, Seattle, Washington.
44. Egli, A. H.; King, L. L.; and St. Clair, T. L.: Semi-Interpenetrating Networks of LARC-TPI. Presented at the 18th National SAMPE Technical Conference, October 7-9, 1986, Seattle, Washington. In Proceedings, Volume 18, p. 440-453.
45. Harris, F. W.; Beltz, M. W.; and Hergenrother, P. M.: A New Readily Processable Polyimide. Presented at the 18th National SAMPE Technical Conference, October 7-9, 1986, Seattle, Washington. In Proceedings, Volume 18, p. 209-219.
46. Hergenrother, P. M.; Havens, S. J.; and Jensen, B. J.: New Polyarylene Ethers. Presented at the 18th National SAMPE Technical Conference, October 7-9, 1986, Seattle, Washington. In Proceedings, Volume 18, p. 454-465.

47. Hergenrother, P. M.; Wakelyn, N. T.; and Havens, S. J.: Polyimides Containing Carbonyl and Ether Connecting Groups. Presented at the 193rd National Meeting of the American Chemical Society, April 5-10, 1987, Denver, Colorado. In Polymer Preprints, Volume 28, No. 1, p. 92-94.
48. Johnston, N. J.; and Hergenrother, P. M.: High Performance Thermoplastics: A Review of Neat Resin and Composite Properties. Presented at the 32nd International SAMPE Symposium and Exhibition, April 6-9, 1987, Anaheim, California. In SAMPE Preprint, Volume 32, p. 1400-1412.
49. Johnston, N. J.; and St. Clair, T. L.: Thermoplastic Matrix Composites: LARC-TPI, Polyimide-Sulfone and Their Blends. Presented at the 18th National SAMPE Technical Conference, October 7-9, 1986, Seattle, Washington. In Proceedings, Volume 18, p. 53-67.
50. Pater, R. H.; Morgan, C.; Chang, A. C.; and Whitley, K. S.: Crosslinking-Property Relationships in PMR Polyimide Composites. I. 288°C Thermo-Oxidative Stability. Presented at the Society of Plastics Engineers 1987 Annual Technical Conference, May 4-7, 1987, Los Angeles, California. SPE Paper No. 466. In Proceedings, p. 1450-1453.
51. Pratt, J. R.; St. Clair, T. L.; Burks, H. D.; and Stoakley, D. M.: Polyimide Processing Additives. Presented at the 32nd International SAMPE Symposium and Exhibition, April 6-9, 1987, Anaheim, California. In SAMPE Preprint, Volume 32, p. 1036-1050.
52. St. Clair, T. L.; Burks, H. D.; Wakelyn, N. T.; and Hou, T-H.: Characterization of Crystalline Polyimide LARC-TPI. Presented at the 193rd National Meeting of the American Chemical Society, April 5-10, 1987, Denver, Colorado. In Polymer Preprints, Volume 28, No. 1, p. 90-91.
53. Young, P. R.; and Chang, A. C.: Cure Study of Soluble Aromatic Polyimide Films. Presented at the 32nd International SAMPE Symposium and Exhibition, April 6-9, 1987, Anaheim, California. In SAMPE Preprint, Volume 32, p. 1051-1062.

#### **Technical Talks**

54. Bascom, W. D.; Cordner, L. W.; Hinkley, J. A.; and Johnston, N. J.: Determination of Carbon Fiber Adhesion to Thermoplastic Polymers Using the Single Fiber Matrix Matrix Tensile Test. Presented at the American Society for Composites First Technical Conference, October 7-9, 1986, Dayton, Ohio.



55. Bass, R. G.; Andrews, S. M.; and Hergenrother, P. M.: High Performance Polymers From the Reaction of Aromatic Dinucleophiles, Aromatic Dipropynones, and Aromatic Bis (Propynoic Esters) . Presented at the American Chemical Society Division of Polymer Chemistry Interdisciplinary Symposium on Recent Advances in Polyimides and Other High Performance Polymers, July 13-16, 1987, Reno, Nevada.
56. Baucom, R. M.: Processing of High Performance Composites. Presented at the SAMPE Old Dominion Chapter Seminar on An Introduction to High Performance Composites, May 7, 1987, Williamsburg, Virginia.
57. Dezern, J. F.: Synthesis and Characterization of BTDA Based Polyamide-imides. Presented at the American Chemical Society Division of Polymer Chemistry Interdisciplinary Symposium on Recent Advances in Polyimides and Other High Performance Polymers, July 13-16, 1987, Reno, Nevada.
58. Hergenrother, P. M.: Advances in Polymer Matrices for Composites. Presented at the Gordon Research Conference on Polymers, June 29 - July 3, 1987, New London, New Hampshire.
59. Hergenrother, P. M.: High Performance Organic Adhesives. Presented at the Adhesion Science Review at Virginia Polytechnic Institute and State University, May 3-6, 1987, Blacksburg, Virginia.
60. Hergenrother, P. M.: High Performance Thermoplastics. Presented at the Air Force Fourth Industry/Government Review of Thermoplastic Matrix Composites, February 9-12, 1987, San Diego, California.
61. Hergenrother, P. M.: High Temperature Organic Adhesives and Composites. Presented at the State University of New York Short Course on High Temperature Polymers: Synthesis, Properties, and Applications, January 19-22, 1987, Tokyo, Japan.
62. Hergenrother, P. M.: High Temperature Organic Adhesives. Presented at the 1987 Plastic Institute of America (PIA) Course on Advances in Adhesion Science and Adhesives, September 28-30, 1987, Boston, Massachusetts.
63. Hergenrother, P. M.: Matrix Chemistry on High Performance Composites. Presented at the SAMPE Old Dominion Chapter Seminar on An Introduction to High Performance Composites, May 7, 1987, Williamsburg, Virginia.
64. Hergenrother, P. M.: Other High Performance Heterocyclic Polymers. Presented at the American Chemical Society Division of Polymer Chemistry Interdisciplinary Symposium on Recent Advances in Polyimides and Other High Performance Polymers, July 13-16, 1987, Reno, Nevada.

65. Hergenrother, P. M.: Other High Temperature Thermoplastics. Presented at the State University of New York Short Course on High Temperature Polymers: Synthesis, Properties, and Applications, January 19-22, 1987, Tokyo, Japan.
66. Hergenrother, P. M.; and Havens, S. J.: New High Temperature Polyimide Adhesives. Presented at the 1987 Tenth International Meeting of the Adhesion Society, February 22-27, 1987, Williamsburg, Virginia.
67. Hergenrother, P. M.; and Havens, S. J.: New Semi-Crystalline Polyimides. Presented at the American Chemical Society Division of Polymer Chemistry Interdisciplinary Symposium on Recent Advances in Polyimides and Other High Performance Polymers, July 13-16, 1987, Reno, Nevada.
68. Hergenrother, P. M.: Polyarylene Ethers. Presented at the Division of Polymer Chemistry, Inc., 13th Biennial Polymer Symposium, November 23-26, 1986, Boca Raton, Florida.
69. Hinkley, J. A.: Fibers and Interfaces in High Performance Composites. Presented at the SAMPE Old Dominion Chapter Seminar on An Introduction to High Performance Composites, May 7, 1987, Williamsburg, Virginia.
70. Jensen, B. J.; Hergenrother, P. M.; and Havens, S. J.: Poly(Arylene Ethers) Containing 9,9-Diphenylfluorene. Presented at the American Chemical Society Division of Polymer Chemistry Interdisciplinary Symposium on Recent Advances in Polyimides and Other High Performance Polymers, July 13-16, 1987, Reno, Nevada.
71. Johnston, N. J.: High Performance Composites: Matrix Property-Composite Property Relationships. Presented at the Sixth International Conference on Composite Materials (ICCM), July 20-24, 1987, London, England.
72. Johnston, N. J.: High Performance Composites Part A: Introduction to Composites Part B: Resin Property-Composite Property Relationships. Presented at the State University of New York at New Paltz Short Course on Principles of High Performance Composites, October 15-17, 1986, Lake Mohonk, New York.
73. Johnston, N. J.: Introduction to High Performance Composites. Presented at the SAMPE Old Dominion Chapter Seminar on An Introduction to High Performance Composites, May 7, 1987, Williamsburg, Virginia.

74. Johnston, N. J.: Polyimides in Aerospace Structural Applications. Presented at the American Chemical Society Division of Polymer Chemistry Interdisciplinary Symposium on Recent Advances in Polyimides and Other High Performance Polymers, July 13-16, 1987, Reno, Nevada.
75. Johnston, N. J.: Recent Composites Work on NASA Langley's Thermoplastic Polyimides. Presented at the Air Force Fourth Industry/Government Review of Thermoplastic Matrix Composites, February 9-12, 1987, San Diego, California.
76. Johnston, N. J.: Resin Property-Composite Property Relationships. Presented at the SAMPE Old Dominion Chapter Seminar on An Introduction to High Performance Composites, May 7, 1987, Williamsburg, Virginia.
77. Johnston, N. J.: Thermoset and Thermoplastic Composites: Room for Both? Presented at the Gordon Research Conference on Thermoset Polymers, June 22-26, 1987, New London, New Hampshire.
78. Johnston, N. J.; and St. Clair, T. L.: Thermoplastic Matrix Composites: LARC-TPI, Polyimide-Sulfone and Their Blends. Presented at the Aerojet-General Composites and Advanced Materials Seminar, December 16-17, 1986, Sacramento, California.
79. Pater, R. H.: Dynamic Mechanical Characterization of High Temperature PMR Polyimides and Composites. Presented at the Michigan State University Dynamic Mechanical Characterization of Polymer Composites Symposium, July 13-14, 1987, East Lansing, Michigan.
80. Pater, R. H.: The Effects of Crosslinking on Physical and Mechanical Properties in PMR Polyimide Composites. Presented at the High Temple Workshop VII, January 26-30, 1987, Sacramento, California.
81. Progar, D. J.; and Pike, R. A.: Adhesive Evaluation of Water-Soluble LARC-TPI. Presented at the Gordon Research Conference on the Science of Adhesion, August 17-21, 1987, New Hampton, New Hampshire.
82. Schwartz, W. T.; Sojka, S. A.; Wolfe, R. A.; St. Clair, T. L.; and Pratt, J. R.: <sup>13</sup>CNMR Correlations of Aromatic Ether Anhydrides and Imides. Presented at the American Chemical Society Division of Polymer Chemistry Interdisciplinary Symposium on Recent Advances in Polyimides and Other High Performance Polymers, July 13-16, 1987, Reno, Nevada.

83. St. Clair, T. L.: Crystalline Polyimide Adhesives. Presented at the Gordon Research Conference on the Science of Adhesion, August 17-21, 1987, New Hampton, New Hampshire.
84. St. Clair, T. L.: Crystallinity in LARC-TPI. Presented at the University of Connecticut Seminar Series on Materials, August 14, 1987, Storrs, Connecticut.
85. St. Clair, T. L.: Developments in Polyimides. Presented at the American Chemical Society Younger Chemist Committee's Emerging Technologies Symposium, April 6, 1987, Denver, Colorado.
86. St. Clair, T. L.: Linear Aromatic Polyimides. Presented at the State University of New York Short Course on High Temperature Polymers: Synthesis, Properties, and Applications, May 7-9, 1987, New Paltz, New York.
87. St. Clair, T. L.: Linear Thermoplastic Polyimides, Part I. Presented at the State University of New York Short Course on High Temperature Polymers: Synthesis, Properties, and Applications, January 19-22, 1987, Tokyo, Japan.
88. St. Clair, T. L.: Linear Thermoplastic Polyimides, Part II. Presented at the State University of New York Short Course on High Temperature Polymers: Synthesis, Properties, and Applications, January 19-22, 1987, Tokyo, Japan.
89. St. Clair, T. L.: NASA Langley Thermoplastic Matrix Program. Presented at the Air Force Fourth Industry/Government Review of Thermoplastic Matrix Composites, February 9-12, 1987, San Diego, California.
90. St. Clair, T. L.: Polymeric Materials Research at LaRC. Presented at the First Annual Meeting of the Society of Polymer Science, Japan, January 20, 1987, Tokyo, Japan.
91. St. Clair, T. L.: Semi-Interpenetrating Polyimide Networks. Presented at the State University of New York Short Course on High Temperature Polymers: Synthesis, Properties, and Applications, May 7-9, 1987, New Paltz, New York.
92. St. Clair, T. L.: Semi-Interpenetrating Polymer Network of Polyimides. Presented at the State University of New York Short Course on High Temperature Polymers: Synthesis, Properties, and Applications, January 19-22, 1987, Tokyo, Japan.

93. St. Clair, T. L.: Semi-Interpenetrating Polyimide Networks. Presented at the American Chemical Society Division of Polymer Chemistry Interdisciplinary Symposium on Recent Advances in Polyimides and Other High Performance Polymers, July 13-16, 1987, Reno, Nevada.
94. St. Clair, T. L.: Structure-Property Relationships in Polyimides. Presented at the American Chemical Society Division of Polymer Chemistry Interdisciplinary Symposium on Recent Advances in Polyimides and Other High Performance Polymers, July 13-16, 1987, Reno, Nevada.

#### **Tech Briefs**

95. Baucom, R. M.; Johnston, N. J.; St. Clair, T. L.; Nelson, J. B.; Gleason, J. R.; and Proctor, K. M.: Preparation of Processable Aromatic Polyimide Thermoplastic Blends. NASA Tech Brief LAR-13695.
96. Delano, C. B.; and Kiskiras, C. J. (Acurex Corporation): Polyimides From BTDA, m-PDA, and HDA. NASA Tech Brief LAR-13635.
97. Hergenrother, P. M. (LaRC); Connell, J. W. (VCU); and Havens, S. J. (PRC Kentron, Inc.) : Acetylene-Terminated Aspartimides and Derived Resins. NASA Tech Brief LAR-13730.
98. Hergenrother, P. M. (LaRC); and Harris, F. W.; and Beltz, M. W. (University of Akron): A New, Readily Processable Polyimide. NASA Tech Brief LAR-13675.
99. St. Clair, T. L.: Process for Developing Crystallinity in Linear Aromatic Polyimides. NASA Tech Brief LAR-13732.
100. St. Clair, T. L.; Burks, H. D.; and Stoakley, D. M. (LaRC); and Pratt, J. R. (PRC Kentron, Inc.): Polyimide Processing Additives. NASA Tech Brief LAR-13669.
101. St. Clair, T. L.; and Singh, J. J. (LaRC); and Pratt, J. R. (PRC Kentron, Inc.): Polyimide Processing Additives for Lowering Free Volume and Moisture Pickup. NASA Tech Brief LAR-13679.
102. Stoakley, D. M.; St. Clair, A. K.; and Little, B. D.: Tensile Film Clamps and Mounting Block for Viscoelastomers. NASA Tech Brief LAR-13696.

## **Patents**

103. Bell, V. L.; and Havens, S. J.: Process for Crosslinking and Extending Conjugated Diene-Containing Polymers. U.S. Patent 4,661,558. Issued April 28, 1987.
104. Egli, A. H.; and St. Clair, T. L.: Semi-2-Interpenetrating Polymer of High Temperature Polymer Systems. U.S. Patent 4,695,610. Issued September 22, 1987.
105. Hergenrother, P. M.; Bass, R. G.; Connell, J. W.; and Sinsky, M. S.: Polylenamines From Aromatic Diacetylenic Diketones and Diamines. U.S. Patent 4,663,483. Issued May 5, 1987.
106. Hergenrother, P. M.; and Havens, S. J.: Ethynyl Terminated Ester Oligomers and Polymers Therefrom. U. S. Patent 4,638,083. Issued January 20, 1987.
107. Hergenrother, P. M.; and Jensen, B. J.: 5-(4-Ethynylphenoxy)Isophthaloyl Chloride. U.S. Patent 4,622,182. Issued November 11, 1986.
108. St. Clair, T. L.; and Maudgal, S. S.: Acetylene (Ethynyle) Terminated Polyimide Siloxan and Process for Preparation Thereof. U.S. Patent 4,624,888. Issued November 25, 1986.

## **FATIGUE AND FRACTURE BRANCH**

### **Quick-Release Technical Memorandums**

109. Crews, J. H., Jr.; and Naik, R. A.: Bearing-Bypass Loading on Bolted Composite Joints. NASA TM-89153, May 1987.
110. Crews, J. H., Jr.; Shivakumar, K. N.; and Raju, I. S.: Factors Influencing Elastic Stresses in Double Cantilever Beam Specimens. NASA TM-89033, November 1986.
111. Johnson, W. S.: Fatigue Damage Accumulation in Various Metal Matrix Composites. NASA TM-89116, March 1987.
112. Johnson, W. S.: Impact and Residual Fatigue Behavior of ARALL and AS6/5245 Composite Materials. NASA TM-89013, October 1986.
113. Johnson, W. S.; and Bigelow, C. A.: Elastic-Plastic Stress Concentrations Around Crack-Like Notches in Continuous Fiber Reinforced Metal Matrix Composites. NASA TM-89093, February 1987.

114. O'Brien, T. K.; Murri, G. B.; and Salpekar, S. A.: Interlaminar Shear Fracture Toughness and Fatigue Thesholds for Composite Materials. NASA TM-89157, AVSCOM TM 87-B-9, August 1987.
115. Poe, C. C., Jr.: A Parametric Study of Fracture Toughness of Fibrous Composite Materials. NASA TM-89100, February 1987.
116. Poe, C. C., Jr.; and Ilg, W.: Strength of a Thick Graphite/Epoxy Rocket Motor Case After Impact by a Blunt Object. NASA TM-89099, February 1987.
117. Raju, I. S.; Crews, J. H., Jr.; and Aminpour, M. A.: Convergence of Strain Energy Release Rate Components for Edge-Delaminated Composite Laminates. NASA TM-89135, April 1987.
118. Raju, I. S.; and Newman, J. C., Jr.: Finite-Element Analysis of Corner Cracks in Rectangular Bars. NASA TM-89070, June 1987.
119. Shivakumar, K. N.; and Crews, J. H., Jr.: Energy Dissipation Associated With Crack Extension in an Elastic-Plastic Material. NASA TM-89032, January 1987.
120. Tan, P. W.; Raju, I. S.; and Newman, J. C., Jr.: Stress-Intensity Factor Calculations Using the Boundary Force Method. NASA TM-89158, June 1987.
121. Whitcomb, J. D.; and Shivakumar, K. N.: Strain-Energy Release Rate Analysis of a Laminate With a Postbuckled Delamination. NASA TM-89091, February 1987.

### **Contractor Reports**

122. Joseph, P. F.; and Erdogan, F.: Plates and Shells Containing a Surface Crack Under General Loading Conditions. (NAG1-713 Lehigh University). NASA CR-178328, July 1987.
123. Raju, I. S.: Q3DG - A Computer Program for Strain-Energy-Release Rates for Delamination Growth in Composite Laminates. (NAS1-17808 Analytical Services and Materials, Inc.) NASA CR-178205, November 1986.
124. Raju, I. S.: Simple Formulas for Strain-Energy-Release Rates With Higher Order and Singular Finite Elements. (NAS1-17808 and NAS1-18256 Analytical Services and Materials, Inc.) NASA CR-178186, December 1986.

125. Wu, B-H; and Erdogan, F.: The Surface Crack Problem in an Orthotropic Plate Under Bending and Tension. (NGR 39-007-011 Lehigh University) NASA CR-178281, April 1987.

#### **Journal Articles and Other Publications**

126. Bigelow, C. A.: Parametric Study of Stress-Intensity Factors in Bonded Composite Stringer Panels. Journal of Engineering Material and Technology, Volume 109, No. 1, January 1987, p. 36-39.
127. Johnson, W. S.: METAL MATRIX COMPOSITES: Their Time to Shine? ASTM Standardization News, Volume 15, No. 10, 1987, p. 36-39.
128. Johnson, W. S.; and Mangalgiri, P. D.: Influence of the Resin on Interlaminar Mixed-Mode Fracture. Toughened Composites, ASTM STP 937, 1987, p. 295-315.
129. Johnson, W. S.; and Mangalgiri, P. D.: Investigation of Fiber Bridging in Double Cantilever Beam Specimens. Journal of Composite Technology and Research, Volume 9, No. 1, Spring 1987, p. 10-13.
130. Kelkar, A.; Elber, W.; and Raju, I. S.: Large Deflection Behavior of Circular Quasi-Isotropic Laminates Under Point Loading. AIAA Journal, Volume 25, No. 1, January 1987, p. 99-106.
131. Liechti, K.; Johnson, W. S.; and Dillard, D. A.: Experimentally Determined Strength of Adhesively Bonded Joints in Joining Fibre-Reinforced Plastics, Chapter 4, F. L. Matthews, ed., Elsevier Applied Science, 1987, p. 105-183.
132. Mangalgiri, P. D.; Johnson, W. S.; and Everett, R. A., Jr.: Effect of Adherend Thickness and Mixed Mode Loading on Debond Growth in Adhesively Bonded Composite Joints. The Journal of Adhesion, Volume 23, 1987, p. 263-288.
133. O'Brien, T. K.: Generic Aspects of Delamination in Fatigue of Composite Materials. Journal of the American Helicopter Society, Volume 32, No. 1, January 1987, p. 13-18.
134. Shivakumar, K. N.; and Crews, J. H., Jr.: Energy Dissipation Associated With Crack Extension in an Elastic-Plastic Material. Engineering Fracture Mechanics, Volume 28, No. 3, 1987, p. 319-330.



## Meeting Presentations

135. Crews, J. H., Jr.; and Naik, R. A.: Bearing-Bypass Loading on Bolted Composite Joints. Presented at the AGARD Structures and Materials Panel Specialists' Meeting on Behaviour and Analysis of Mechanically Fastened Joints in Composite Structures, April 27-29, 1987, Madrid, Spain.
136. Everett, R. A., Jr.: Review of Fatigue and Fracture Research at NASA Langley Research Center. Presented at the 1987 NASA/Army Rotorcraft Technology Conference, March 17-19, 1987, Moffett Field, California. NASA CP pending.
137. Johnson, W. S.: Impact and Residual Fatigue Behavior of ARALL and AS6/5245 Composite Material. Presented at the 1986 ASME Winter Annual Meeting, December 7-12, 1986, Anaheim, California. Proceedings pending.
138. Johnson, W. S.: Prediction of Laminate Properties and Usage Limits for Advanced Metal Matrix Composites Considered for NASP Applications. Presented at the Third National Aero-Space Plane Technology Symposium, June 2-4, 1987, Moffett Field, California. NASA CP-3019, Volume IV, p. 141-159.
139. Newman, J. C., Jr.; Phillips, E. P.; and Swain, M. H.: Predicting the Growth of Small and Large Cracks Using a Crack-Closure Model. Presented at the Chinese Societies of Metals, Aeronautics and Astronautics, and Mechanics Fifth International Conference on Mechanical Behaviour of Materials, June 3-6, 1987, Beijing, China. In Proceedings, Volume 1, p. 51-60.
140. O'Brien, T. K.: Delamination Durability of Composite Materials for Rotorcraft. Presented at the 1987 NASA/Army Rotorcraft Technology Conference, March 17-19, 1987, Moffett Field, California. NASA CP pending.
141. O'Brien, T. K.: Fatigue Delamination Behavior of PEEK Thermoplastic Composite Laminates. Presented at the American Society for Composites First Conference on Composite Materials, October 7-9, 1986, Dayton, Ohio. In Proceedings, p. 404-420.
142. Poe, C. C., Jr.: A Parametric Study of Fracture Toughness of Fibrous Composite Materials. Presented at the ASME Sixth International Symposium on Offshore Mechanics and Arctic Engineering (OMAE), March 1-5, 1987, Houston, Texas. ASME Paper No. OMAE-87-602. In Proceedings, Volume III, p. 15-24.

143. Poe, C. C., Jr.; and Ilg, W.: Tensile Strength of a Thick Graphite/Epoxy Rocket Motor Case After Impact by a Blunt Object. Presented at the 1987 NASA/JANNAF Composite Motor Case Subcommittee Technical Exchange Meeting, February 23-27, 1987, Hampton, Virginia. In CPIA Publication 460, p. 179-202.
144. Raju, I. S.; Shivakumar, K. N.; and Crews, J. H., Jr.: Three-Dimensional Stress Analysis of a Composite Double Cantilever Beam Specimen. Presented at the AIAA/ASME, et al., 28th Structures, Structural Dynamics and Materials Conference, April 6-8, 1987, Monterey, California. AIAA Paper No. 87-0864-CP.
145. Tan, P. W.; and Bigelow, C. A.: Analysis of Cracked Laminates With Holes Using the Boundary Force Method. Presented at the AIAA/ASME, et al., 28th Structures, Structural Dynamics and Materials Conference, April 6-8, 1987, Monterey, California. AIAA Paper No. 87-0862-CP.
146. Tan, P. W.; Raju, I. S.; and Newman, J. C., Jr.: Boundary Force Method Analysis of Notched Plates With Cracks. Presented at the International Union of Theoretical and Applied Mechanics Symposium on Advanced Boundary Element Methods, April 13-16, 1987, San Antonio, Texas. Proceedings pending.
147. Whitcomb, J. D.; and Shivakumar, K. N.: Strain-Energy Release Rate Analysis of a Laminate With a Postbuckled Delamination. Presented at the Fourth International Conference on Numerical Methods in Fracture Mechanics, March 23-27, 1987, San Antonio, Texas. In Proceedings, p. 581-605.

#### Technical Talks

148. Guynn, E. G.; Bradley, W. L.; and Elber, W.: Micromechanics of Compression Failures in Composite Laminates. Presented at the ASTM Second Symposium on Composite Materials: Fatigue and Fracture, April 27-28, 1987, Cincinnati, Ohio.
149. Johnson, W. S.: Fatigue of Metal Matrix Composites. Presented at the Fourth Annual Review of Research and Educational Activities of the Center for Composite Materials and Structures, May 11-13, 1987, Blacksburg, Virginia.
150. Johnson, W. S.; and Bigelow, C. A.: Elastic-Plastic Stress Concentrations Around Notches in Continuous Fiber-Reinforced Metal-Matrix Composites. Presented at the ASTM Second Symposium on Test Methods and Design Allowables for Fiber Composites, November 3-4, 1986, Phoenix, Arizona.

151. Johnson, W. S.; Mangalgiri, P. D.; and Everett, R. A., Jr.: Effect of Adherend Thickness and Mixed Mode Loading on Debond Growth in Adhesively Bonded Composite Joints. Presented at the 1987 Tenth International Meeting of the Adhesion Society, February 22-27, 1987, Williamsburg, Virginia.
152. Newman, J. C., Jr.: Analytical Modeling of Fatigue-Crack Growth. Presented at the University of Virginia, National Science Foundation, et al., Third International Conference on Fatigue and Fracture Threshold, June 28-July 3, 1987, Charlottesville, Virginia.
153. O'Brien, T. K.: Test and Evaluation Methods for High Performance Composites. Presented at the SAMPE Old Dominion Chapter Seminar on An Introduction to High Performance Composites, May 7, 1987, Williamsburg, Virginia.
154. O'Brien, T. K.; Murri, G. B.; and Salpekar, S. A.: Interlaminar Shear Fracture Toughness and Fatigue Thresholds for Composite Materials. Presented at the ASTM Second Symposium on Composite Materials: Fatigue and Fracture, April 27-28, 1987, Cincinnati, Ohio.
155. Poe, C. C., Jr.: Application of Fracture Mechanics to Impact Damage in Thick Walled Pressure Vessels. Presented at the 1986 Winter Annual Meeting, December 7-12, 1986, Anaheim, California.
156. Poe, C. C., Jr.: Fracture of Boron/Aluminum Laminates With Various Proportions of 0° and 45° Plies. Presented at the 1986 ASME Winter Annual Meeting, December 7-12, 1986, Anaheim, California.
157. Poe, C. C., Jr.; and Ilg, W.: Effect of Impacts by a Blunt Object on Strength of a Thick Graphite/Epoxy Rocket Motor Case. Presented at the ASTM Second Symposium on Test Methods and Design Allowables for Fiber Composites, November 3-4, 1986, Phoenix, Arizona.
158. Raju, I. S.; Atluri, S. N.; and Newman, J. C., Jr.: Stress-Intensity Factors for Small Surface and Corner Cracks. Presented at the 20th National Symposium on Fracture Mechanics: Perspectives and Directions, June 23-25, 1987, Bethlehem, Pennsylvania.
159. Raju, I. S.; Crews, J. H., Jr.; and Aminpour, M. A.: Strain-Energy Release Rate Analyses of Edge Delaminated Composites. Presented at the Fourth International Conference on Numerical Methods in Fracture Mechanics, March 23-27, 1987, San Antonio, Texas.

160. Shivakumar, K. N.; and Newman, J. C., Jr.: Numerical Fracture Simulation of Bend Specimens. Presented at the Fourth International Conference on Numerical Methods in Fracture Mechanics, March 23-27, 1987, San Antonio, Texas.

### **Tech Briefs**

161. Raju, I. S. (Analytical Services and Materials, Inc.): Q3DG: A Computer Program for Strain-Energy Release Rate for Delamination Growth in Composite Laminates. NASA Tech Brief LAR-13698.

## **APPLIED MATERIALS BRANCH**

### **Formal Reports**

162. Dries, G. A.; and Tompkins, S. S.: Effects of Thermal Cycling on Graphite-Fiber-Reinforced 6061 Aluminum. NASA TP-2612, October 1986.
163. Dries, G. A.; and Tompkins, S. S.: Effects of Thermal Cycling on Thermal Expansion and Mechanical Properties of Several Graphite-Reinforced Aluminum Metal-Matrix Composites. NASA TP-2701, July 1987.
164. Long, E. R., Jr.; and Long, S. A. T.: Spectroscopic Comparison of Effects of Electron Radiation on Mechanical Properties of Two Polyimides. NASA TP-2663, April 1987.
165. Maahs, H. G.; Ransone, P. O.; and Yamaki, Y. R.: Evolution of Microstructure, Pore Size, and Interlaminar Strength of ACC-Type Carbon-Carbon With Successive Densification. NASA TP-2754, September 1987.
166. Ohlhorst, C. W.; and Ransone, P. O.: Effects of Thermal Cycling on Thermal Expansion and Interlaminar Mechanical Properties of Advanced Carbon-Carbon Composites. NASA TP-2734, August 1987.

### **Quick-Release Technical Memorandums**

167. Dexter, H. B.: Long-Term Environmental Effects and Flight Service Evaluation of Composite Materials. NASA TM-89067, January 1987.
168. Farley, G. L.: A Method of Predicting the Energy-Absorption Capability of Composite Subfloor Beams. NASA TM-89088, AVSCOM TM 87-B-4, March 1987.

169. Farley, G. L.: Energy-Absorption Capability and Scalability of Square Cross Section Composite Tube Specimens. NASA TM-89087, AVSCOM TM 87-B-3, March 1987.
170. Farley, G. L.: The Effects of Crushing Speed on the Energy-Absorption Capability of Composite Material. NASA TM-89122, AVSCOM TR 87-B-1, March 1987.
171. Witte, W. G.: Baseline Tensile Tests of Composite Materials for LDEF Exposure. NASA TM-89069, March 1987.

### **Contractor Reports**

172. Clarke, W. A.; Eitman, D. A.; Ketterer, M. E.; and Wesley, J. L.: Inhibited Filament, Oxidation-Resistant Carbon-Carbon Composites. (NAS1-17957 Science Applications International Corporation) NASA CR-178177, June 1986 (Released 1987).
173. Coggeshall, R. L.: 737 Graphite Composite Flight Spoiler Flight Service Evaluation. (NAS1-11668 Boeing Commercial Airplane Company) NASA CR-178322, August 1987.
174. Dow, N. F.; Ramnath, V.; and Rosen, B. W.: Analysis of Woven Fabrics for Reinforced Composite Materials. (NAS1-17205 Materials Sciences Corporation) NASA CR-178275, August 1987.
175. Kerr, J. R.; and Haskins, J. F.: Time-Temperature-Stress Capabilities of Composite Materials for Advanced Supersonic Technology Application. (NAS1-12308 General Dynamics Corporation) NASA CR-178272, May 1987.
176. Stone, R. H.: Flight Service Evaluation of Advanced Composite Ailerons on the L-1011 Transport Aircraft - Fifth Annual Flight Report. (NAS1-15069 Lockheed-California Company) NASA CR-178321, June 1987.

### **Journal Articles and Other Publications**

177. Bowles, D. E.; Tompkins, S. S.; and Sykes, G. F., Jr.: Electron Radiation Effects on the Thermal Expansion of Graphite Resin Composites. Journal of Spacecraft and Rockets, Volume 23, No. 6, November - December 1986, p. 625-629.
178. Bowles, D. E.; and Tenney, D. R.: Composite Tubes for the Space Station Truss Structure. SAMPE Journal, Volume 23, No. 3, May/June 1987, p. 49-57.

179. Funk, J. G.; and Sykes, G. F., Jr.: The Effects of Radiation on the Interlaminar Fracture Toughness of a Graphite/Epoxy Composite. Journal of Composites Technology and Research, Volume 8, No. 3, Fall 1986, p. 92-97.
180. Hyer, M. W.; Cooper, D. E.; Cohen, D.; and Tompkins, S. S.: Temperature and Deflection Data From the Asymmetric Heating of Cross-Ply Composite Tubes. Journal of Composites Technology and Research, Volume 9, No. 1, Spring 1987, p. 14-20.
181. Long, S. A. T.; Long, E. R., Jr.; Ries, H. R.; and Harries, W. L.: Electron-Radiation Effects on the AC and DC Electrical Properties and Unpaired Electron Densities of Three Aerospace Polymers. IEEE Transactions on Nuclear Science, Volume NS-33, No. 6, December 1986, p. 1390-1395.
182. Prasad, C. B.; Prabhakaran, R.; and Tompkins, S. S.: Determination of Calibration Constants for the Hole-Drilling Residual Stress Measurement Technique Applied to Orthotropic Composites - Part I: Theoretical Considerations. Composite Structures, Volume 8, No. 2, 1987, p. 105-118.
183. Tompkins, S. S.: Thermal Expansion of Selected Graphite-Reinforced Polyimide-, Epoxy-, and Glass-Matrix Composites. International Journal of Thermophysics, Volume 8, No. 1, January 1987, p. 119-132.

### **Meeting Presentations**

184. Baker, D. J.: Evaluation of Composite Components on the Bell 206L and Sikorsky S-76 Helicopters. Presented at the 1986 SAE Aerospace Technology Conference & Exposition, October 13-16, 1986, Long Beach, California. SAE Paper No. 86-1671.
185. Bowles, D. E.; and Tenney, D. R.: Composite Tubes for the Space Station Truss Structure. Presented at the 18th National SAMPE Technical Conference, October 7-9, 1986, Seattle, Washington. In Proceedings, Volume 18, p. 414-428.
186. Bradbury, C. A.; Harries, W. L.; Long, E. R., Jr.; and Long, S. A. T.: Improvement of ATR IR Spectroscopy for Use With Solid Samples. Presented at the 1986 Annual Meeting of the Southeastern Section of the American Physical Society, November 20-22, 1986, Williamsburg, Virginia. Abstract published in APS Bulletin, Volume 31, No. 10, November 1986, p. 1771.
187. Deaton, J. W.: Residual Strength of Repaired Graphite/Epoxy Laminates After 3 Years of Outdoor Exposure. Presented at the Second DOD/NASA Composites Repair Technology Workshop, November 3-6, 1986, San Diego, California. Proceedings pending.

Diego, California. Proceedings pending.

188. Dries, G. A.; and Tompkins, S. S.: Thermal Expansion and Mechanical Properties of Continuous Graphite Fiber Reinforced Aluminum Metal-Matrix Composite. Presented at the 18th National SAMPE Technical Conference, October 7-9, 1986, Seattle, Washington. In Proceedings, p. 56-71.
189. Farley, G. L.: A Method of Predicting the Energy-Absorption Capability of Composite Subfloor Beams. Presented at the AIAA/ASME, et al., 28th Structures, Structural Dynamics and Materials Conference, April 6-8, 1987, Monterey, California. AIAA Paper No. 87-0800-CP.
190. Farley, G. L.: Energy Absorption in Composite Materials for Crashworthy Structures. Presented at the Sixth International Conference on Composite Materials (ICCM), July 20-24, 1987, London, England. In Proceedings, Volume 3, p. 357-366.
191. Farley, G. L.: Energy Absorption of Composite Material and Structure. Presented at the American Helicopter Society 43rd Annual Forum and Technology Display, May 18-20, 1987, St. Louis, Missouri. In Proceedings, Volume II, p. 613-627.
192. Farley, G. L.; Boitnott, R. L.; and Carden, H. D.: Helicopter Crashworthiness Research Program. Presented at the 1987 NASA/Army Rotorcraft Technology Conference, March 17-19, 1987, Moffett Field, California. NASA CP pending.
193. Ferguson, M. W.; Long, S. A. T.; and Long, E. R., Jr.: Effects of 1-MeV Electrons on Graphite/Polyetherimide Composites. Presented at the 1986 Meeting of the Southeastern Section of the American Physical Society, November 20-22, 1986, Williamsburg, Virginia. Abstract published in APS Bulletin, Volume 31, No. 10, November 1986, p. 1770.
194. Hawkins, D. S.; Mosher, J. J.; Kiefer, R. L.; and Sykes, G. F., Jr.: The Effects of a Dose Rate, Temperature, and Post-Irradiation Handling on a Radiated Polysulfone and Polyetherimide. Presented at the 193rd National Meeting of the American Chemical Society, April 5-10, 1987, Denver, Colorado. In Polymer Preprints, Volume 28, No. 1, p. 112-113.
195. Maahs, H. G.; Ransone, P. O.; and Yamaki, Y. R.: Evolution of Pore Size and Microstructure of ACC-Type Carbon-Carbon With Successive Densifications. Presented at the ACS 11th Annual Conference on Composites and Advanced Ceramic Materials, January 18-21, 1987, Cocoa Beach, Florida. In NASA CP-2482, p. 283-310.

196. Maahs, H. G.; Stroud, C. W.; and Scotti, S. J.: Thin Structural Carbon-Carbon for Control-Surface Applications. Presented at the Second National Aero-Space Plane Technology Symposium, November 5-7, 1986, Laurel, Maryland. Paper No. 122. In NASP CP-2015.
197. Ransone, P. O.; Maahs, H. G.; Ohlhorst, C. W.; and Sawyer, J. W.: Interlaminar Tensile Test Methodology for Two-Directional Carbon-Carbon Composites. Presented at the ACS 11th Annual Conference on Composites and Advanced Ceramic Materials, January 18-21, 1987, Cocoa Beach, Florida. In NASA CP-2482, p. 253-266.
198. Ries, H. R.; Bradbury, C.A.; Harries, W. L.; Long, S. A. T.; and Long, E. R., Jr.: EPR, IR, and Tg Analyses of Electron-Irradiated Polyethylene Terephthalate. Presented at the 1986 Meeting of the Southeastern Section of the American Physical Society, November 20-22, 1986, Williamsburg, Virginia. Abstract published in APS Bulletin, Volume 31, No. 10, November 1986, p. 1770.
199. Stein, B. A.; and Bowles, D. E.: Advanced Composite Materials for Precision Space Structures. Presented at the NASA/JPL Asilomar III Large Deployable Reflector Conference, September 8-10, 1987, Pacific Grove, California. Proceedings pending.
200. Stein, B. A.; Maahs, H. G.; and Brewer, W. D.: Airframe Materials for Hypersonic Vehicles. Presented at the ACS 11th Annual Conference on Composites and Advanced Ceramic Materials, January 18-21, 1987, Cocoa Beach, Florida. In NASA CP-2482, p. 1-23.
201. Sykes, G. F., Jr.; Funk, J. G.; and Slemp, W. S.: Assessment of Space Environment Induced Microdamage in Toughened Composite Materials. Presented at the 18th National SAMPE Technical Conference, October 7-9, 1986, Seattle, Washington. In Proceedings, Volume 18, p. 520-534.
202. Sykes, G. F., Jr.; Hoogstraten, C. A.; Slemp, W. S.; and Hergenrother, P. M.: Simulated Space Environment Effects on the Optical Properties of Poly (ARYLENE ETHERS). Presented at the 193rd National Meeting of the American Chemical Society, April 5-10, 1987, Denver, Colorado. In Polymer Preprints, Volume 28, No. 1, p. 58-60.
203. Tompkins, S. S.; Ard, K. E.; and Sharp, G. R.: Thermal Expansion Behavior of Graphite/Glass and Graphite/Magnesium. Presented at the 18th National SAMPE Technical Conference, October 7-9, 1986, Seattle, Washington. In Proceedings, Volume 18, p. 623-637.



## Technical Talks

204. Bradbury, C. A.; Harries, W. L.; Long, S. A. T.; and Long, E. R., Jr.: Damage Effects of Threshold Doses of Electron Radiation on PEI, PEEI, PET, and PC. Presented at the 1987 Annual Meeting of the Division of Atomic, Molecular, and Optical Physics of the American Physical Society, May 18-20, 1987, Cambridge, Massachusetts.
205. Dexter, H. B.: Aircraft Materials and Structures Technology. Presented at the SAE General Aviation Aircraft Meeting and Exposition, April 28 - May 1, 1987, Wichita, Kansas.
206. Dexter, H. B.: Development of Advanced Structural Materials - Present and Future. Presented at the Purdue University Short Course on Engine-Airframe Integration, July 27-31, 1987, West Lafayette, Indiana.
207. Dexter, H. B.: Overview of Materials and Structures Technology. Presented at the 1987 NASA/Army Rotorcraft Technology Conference, March 17-19, 1987, Moffett Field, California.
208. Long, S. A. T.; Long, E. R., Jr.; Gray, S. L.; and Collins, W. D.: Total Dose and Dose Rate Effects in Electron-Irradiated Polyetherimide. Presented at the American Physical Society 1987 Meeting of the Division of High Polymer Physics, March 16-20, 1987, New York, New York.
209. Maahs, H. G.; and Sawyer, J. W.: Research Needs for Carbon-Carbon Composites - NASA-LaRC Perspective. Presented at the Office of Naval Research Review/Workshop on Carbon-Carbon Composites, March 18-19, 1987, Arlington, Virginia.
210. Maahs, H. G.; and Yamaki, Y.R.: Effect of Fiber Surface Treatment Level on Interlaminar Strengths of Carbon-Carbon Composites. Presented at the Interagency Planning Group Meeting on Reinforcement-Matrix Interactions in Carbon-Carbon, July 16-17, 1987, Arlington, Virginia.
211. Ries, H. R.; Long, S. A. T.; Long, E. R., Jr., and Harries, W. L.: EPR and DC Conductivity Analyses of an Electron-Irradiated Polyimide. Presented at the 1987 Spring General Meeting of the American Physical Society, April 20-23, 1987, Crystal City, Virginia.
212. Stein, B. A.: Space Station Materials Technology. Presented at the Space Station Advanced Development Program Technical Review, October 29, 1986, Huntsville, Alabama.

213. Stroud, C. W.: Environmental Simulator Facility Applied to Oxidative Testing of Carbon-Carbon Composites. Presented at the High Temperature Testing of Materials Meeting, November 12-13, 1986, Alexandria, Virginia.

#### **Tech Briefs**

214. Farley, G. L.: Crash Energy Absorbing Composite Sub-Floor Structure. NASA Tech Brief LAR-13697.
215. Farley, G. L.; Mantay, W. R.; and Starnes, J. H., Jr.: Structurally Tailorable, Nonlinear, Snap-Through Spring. NASA Tech Brief LAR-13729.

#### **Patents**

216. Tompkins, S. S.; and Dries, G. A.: Method of Thermal Strain Hysteresis Reduction in Metal Matrix Composites. U.S. Patent 4,662,955. Issued May 5, 1987.

### **Metallic Materials Branch**

#### **Formal Reports**

217. Blackburn, L. B.: Effect of LID Processing on the Microstructure and Mechanical Properties of Ti-6Al-2Sn-4Zr-2Mo Titanium Foil-Gauge Materials. NASA TP-2677, April 1987.
218. Ossa, W. A.; and Royster, D. M.: Material Characterization of Superplastically Formed Titanium (Ti-6Al-2Sn-4Zr-2Mo) Sheet. NASA TP-2674, May 1987.

#### **Contractor Reports**

219. Fischler, J. E.: Studies of the Benefits of Metal Matrix Composites for Advanced Supersonic Cruise Vehicles. (NAS1-16147 McDonnell Douglas Corporation) NASA CR-178325, July 1987.
220. Ray, R.; and Jha, S. C.: Advanced Powder Metallurgy Aluminum Alloys Via Rapid Solidification Technology - Phase II. (NAS1-18001 Marko Materials, Inc.) NASA CR-178356, April 1987.
221. Sankaran, K. K.: Consolidation Processing Parameters and Alternative Processing Methods for Powder Metallurgy Al-Cu-Mg-X-X Alloys. (NAS1-16967 McDonnell Douglas Astronautics Company) NASA CR-178227, February 1987.

## **Journal Articles and Other Publications**

222. Clark, R. K.; Cunnington, G. R., Jr.; and Robinson, J. C.: Vapor-Deposited Emittance-Catalysis Coatings for Superalloys in Heat-Shield Applications. Journal of Thermophysics and Heat Transfer, Volume 1, No. 1, January 1987, p. 28-34.
223. Unnam, J.; Shenoy, R. N.; and Clark, R. K.: Oxidation of Commercial Purity Titanium. Oxidation of Metals, Volume 26, Nos. 3/4, October 1986, p. 231-252.
224. Wagner, J. A.: Mechanical Behavior of 18 Ni 200 Grade Maraging Steel at Cryogenic Temperatures. Journal of Aircraft, Volume 23, No. 10, October 1986, p. 744-749.
225. Weidemann, K. E.; Unnam, J.; and Clark, R. K.: Computer Program for Deconvoluting Powder Diffraction Spectra. Journal of Powder Diffraction, Volume 2, No. 3, September 1987, p. 137-145.
226. Weidemann, K. E.; Unnam, J.; and Clark, R. K.: Deconvolution of Powder Diffraction Spectra. Journal of Powder Diffraction, Volume 2, No. 3, September 1987, p. 130-136.

## **Meeting Presentations**

227. Royster, D. M.; Bales, T. T.; and Davis, R. C.: Superplastic Forming/Weld-Brazing of Ti-6Al-4V Panels for Enhanced Structural Efficiency. Presented at the First International SAMPE Metals and Metals Processing Conference, August 18-20, 1987, Cherry Hill, New Jersey. Proceedings pending.

## **Technical Talks**

228. Blackburn, L. B. B.; Cassada, W.; Colvin, G.; and Starke, E. A., Jr.: The Effect of Processing on the Microstructure, Strength, and Fracture Behavior of Aluminum-Lithium Alloys. Presented at the ASM Aluminum-Lithium Symposium, March 25-26, 1987, Los Angeles, California.
229. Domack, M. S.: Stress Corrosion Evaluation of Powder Metallurgy Aluminum Alloy 7091 With the Breaking Load Test Method. Presented at the Air Force Wright Aeronautical Laboratories Material Laboratory Tri-Service Corrosion Conference, May 5-7, 1987, Colorado Springs, Colorado.

## **Tech Briefs**

230. Unnam, J. (Analytical Services and Materials, Inc.); and Clark, R. K.: Oxygen Barrier Coating for Titanium. NASA Tech Brief LAR-13474.

## **Patents**

231. Unnam, J.; Clark, R. K.: Oxygen Diffusion Barrier Coating. U.S. Patent 4,681,818. Issued July 21, 1987.

## **FY 88 PLANS**

### **Polymeric Materials Branch**

Major research thrusts for FY 88 in the Polymeric Materials Branch are in the areas of resin-matrix composite studies and high performance polymers. Plans for this research are outlined in figure 43. Plans include the synthesis and characterization of neat resins and their composites and the study of prepregging and processing of new matrices into composite materials. Also, the preparation of a series of new semi-crystalline imide copolymers having properties equivalent to or superior to the best available polyimide is planned. This research will be conducted under the following two RTR's:

#### **RTR 505-63-01-01 Resin-Matrix Composite Studies**

##### **Objective:**

Develop and evaluate new damage tolerant, durable high performance composites for advanced structural applications.

##### **Approach:**

Synthesize, characterize and evaluate new/improved moderate and high temperature thermoplastics, semi-crystalline polymers and hybrid thermoplastic/thermosets and their carbon fiber composites. Study prepregging and processing of new matrices into composite materials, including development of new processes and processing equipment. Conduct initial evaluation of new composites, including thermal, thermomechanical, and fracture toughness studies. Support micromechanical analysis program by providing appropriate composites and characterization studies.

##### **Milestones:**

- Complete synthesis and characterization of thermally stable core shell rubbers and determine their efficacy as toughening agents for high temperature polymers - March 1988.
- Prepare large quantity (up to 20 lbs.) of the most promising experimental

advanced resin - May 1988.

- Determine thermal, thermomechanical and fracture toughness properties of the most promising experimental advanced composite matrix material - July 1988.
- Complete Phase II modification of Murdock prepregging machine; demonstrate machine capability with research thermoplastic - August 1988.
- Determine feasibility of powder electrodeposition coating of carbon fiber as a viable prepregging technique - September 1988.

### **RTR 506-43-11-01 High Performance Polymers**

#### **Objective:**

Develop high performance polymers as adhesives, composite matrices, and films for use in high temperature environments.

#### **Approach:**

Synthesize new polymers with an attractive combination of properties and evaluate as high temperature adhesives, composite matrices and films.

#### **Milestones:**

- Evaluate composite properties of a more processable polyimide sulfone containing a low molecular weight non-reactive imide - January 1988.
- Synthesize new polyimides from isomeric oxydiphthalic dianhydrides - February 1988.
- Improve the processability of a semi-crystalline polyimide ( LARC-CPI) and evaluate as an adhesive and composite matrix - April 1988.
- Obtain composite properties on blends of acetylene imidothioethers and acetylene terminated polysulfones - May 1988.
- Optimize molecular weight and processing characteristics of LARC-TPI for sandwich structure - June 1988.
- Prepare a series of new semi-crystalline imide copolymers having a favorable combination of properties - July 1988.
- Complete crystallographic study on crystalline polyimides - August 1988.
- Develop understanding of crosslink density/morphology/toughness relationship in high temperature thermosets - September 1988.

## **Fatigue and Fracture Branch**

Composites research in the Fatigue and Fracture Branch for FY 88 will focus on micromechanics and multidirectional materials. The emphasis in metals research will be on advanced Al alloys and metal-matrix composites. Plans for this research are outlined in figure 44. The research will be carried out under the following three RTR's:

### **RTR 505-63-01-05 Fatigue and Fracture - Composites and Metals**

#### **Objective:**

Develop micromechanical models to predict composite delamination toughness for guidance in the development of second-generation composites. Develop analysis methods to predict cyclic load endurance of aerostructural materials.

#### **Approach:**

Develop testing methods and elasto-plastic 3-D analyses to identify determination failure modes in matrix materials. For metallic structures similar analyses are developed to describe growth for small cracks.

#### **Milestones:**

- Complete microfracture analyses of delamination in mode I, mode II, and combined modes - February 1988.
- Fully integrate the 2-D Boundary Force Method for computing stress intensity factors into the fracture control analysis computer program (FLAGRO) - June 1988.
- Complete mode I cyclic delamination tests with PEEK laminate - July 1988.
- Complete AGARD small-cracks supplemental program on steel, Al-Li, and Ti alloys - September 1988.
- Complete testing of American and Chinese aluminum alloys in NASA/CAE small-cracks program - September 1988.

### **RTR 506-43-11-04 Damage Tolerance of Composites**

#### **Objective:**

To develop unified rational methodologies for the analysis and prevention of cracking damage in composites.

#### **Approach:**

Development of data and new analytical models based on fracture mechanics will make both tension and compression failures more tractable in composites.

Milestones:

- Evaluate viscoelasticity effects on compression failure of notched laminates - February 1988.
- Complete combined analytical and experimental study of instability delamination - March 1988.
- Evaluate existing elasticity solutions for predicting impact damage depth in thick laminates - August 1988.

**RTR 506-43-71-03 Fatigue and Fracture - High Temperature Materials**

Objective:

Develop analytical models to predict fatigue and fracture of high-temperature aerostructural materials.

Approach:

Develop testing methods, elastoplastic micromechanics stress analyses, and failure criteria for high-temperature composites. Incorporate the failure criteria into stress analyses to develop fracture micromechanics models for fatigue and fracture.

Milestones:

- Order apparatus to upgrade test machines for high-temperature testing - November 1987.
- Begin fatigue and fracture testing of MMC materials - April 1988.

**Applied Materials Branch**

Research emphasis in the Applied Materials Branch for FY 88 will be in the areas of carbon-carbon composites, low expansion resins for precision reflectors, and multidirectional, multilayered textile forms. Plans for this research are outlined in figure 45. This research will be carried out under the following five RTR's:

**RTR 505-63-01-06 Composites for Rotorcraft/Aircraft Structures**

Objective:

Develop the technology for the application of advanced composite materials and innovative design concepts in rotorcraft and aircraft structures in order to improve performance, efficiency, damage tolerance, environmental durability, and energy absorption capability compared to metal structures.

Approach:

In-house, contractual, and grant studies will be conducted to develop innovative material forms, and processing science concepts for lightweight composite structure applications. Residual properties after environmental exposures and degradation mechanisms will be determined. Included will be studies on fabrication of near net-shape structural forms using automated textile processes such as weaving, braiding, knitting, and stitching. Composite structural elements fabricated by resin transfer molding and pultrusion processes will be evaluated. Improvements in through-the-thickness properties and damage tolerance will be studied.

Milestones:

- Complete mechanical property characterization of triaxial fabric - November 1987.
- Complete specimen fabrication for investigation of through-the-thickness stitching and resin transfer molding - December 1987.
- Conduct 1/4 lifetime fatigue tests on repaired graphite/epoxy components after 4 years of outdoor sustained-load exposure at NASA Langley - December 1987.
- Award contract to hot-filament wind thermoplastic composite materials - December 1987.
- Characterize thermoplastic panels fabricated with co-mingled thermoplastic woven fabric, thermoplastic films, and thermoplastic prepreg tape - December 1987.
- Demonstrate the capability of in-process ultrasonics to measure voids in composites fabricated in autoclave and pultruder - March 1988.
- Award 4 year task assignment contract to fabricate and inspect composite materials for in-house evaluation - March 1988.
- Complete 1 year of flight service of DC-10 graphite/epoxy vertical stabilizer - March 1988.
- Establish and initiate use of pultrusion methodology for fabrication of thermoplastic resin composites - March 1988.
- Complete 15 years of flight service of B-737 graphite/epoxy spoilers - June 1988.



- Demonstrate the capability to weave composite preforms with multilayer bias plies - June 1988.
- Evaluate the effects of included angle on the energy absorption capability of composite tubes and beams - June 1988.
- Complete evaluation of cruciform in-plane shear test specimen - June 1988.
- Establish baseline property data for pultruded composites and refine the fabrication process - September 1988.
- Develop process model for resin infiltration of woven fabrics - September 1988.
- Demonstrate dielectric process monitor for optimization of resin infiltration into woven fabrics - September 1988.

#### **RTR 506-43-21-04 Composite Materials for Spacecraft Applications**

##### **Objective:**

Develop new composite materials and protective/thermal control coatings for enhanced environmental and thermal-mechanical durability in long-life space structures.

##### **Approach:**

Advanced polymeric-, metallic-, and ceramic-matrix, fiber-reinforced composites will be developed and evaluated for long-term use in spacecraft structures. Evaluation will include thermal cycling, UV and atomic oxygen to simulate the GEO environment. Advanced laser interferometry will be used to determine dimensional stability. Thin metallic and oxide protective coatings will be evaluated on flat and tubular surfaces. The optical, chemical, and mechanical property degradation will be characterized and analytically modeled. Shuttle experiments will be used to verify models and laboratory simulations.

##### **Milestones:**

- Develop aluminum foil anodizing process for producing tailorable optical coatings for composite tubes - March 1988.
- Determine effects of long-term thermal cycling on the adherence and optical properties of anodized aluminum coatings on graphite/epoxy composite tubes - June 1988.
- Determine threshold doses of electron radiation for adverse effects on thermoplastic polymer films - June 1988.

## **RTR 506-43-71-02 Carbon-Carbon Composites**

### **Objective:**

Develop high-strength, minimum gauge, oxidation-protected carbon-carbon materials for hot structure and TPS applications in advanced space transportation vehicles and hypersonic aircraft.

### **Approach:**

Advanced processing methods, alternate precursor materials, fiber surface modifications, and alternate reinforcement concepts will be developed to improve substrate mechanical properties. Matrix and fiber oxidation inhibitors, sealants, and advanced coatings will be developed to improve oxidation resistance. Environmental testing will be performed in simulated mission dynamic environments and in multiparameter (temperature, pressure, load) facilities.

### **Milestones:**

- Key processing parameters for phenolic-based carbon-carbon composites defined for simplified processing and improved interlaminar strengths - September 1988.
- Through-the-thickness reinforcement concepts evaluated for thin-gauge carbon-carbon composites - September 1988.

## **RTR 585-02-21-01 Advanced Materials for Precision Segmented Reflectors**

### **Objective:**

Develop advanced composite materials and coatings that are durable and have stable thermal and mechanical properties in the space service environment of precision segmented reflector spacecraft.

### **Approach:**

New, novel low expansion polymer resins will be developed and used to fabricate composites. Advanced, highly stable graphite/glass laminates using low temperature fabrication methods will be developed. Material constitutive equations and analytical models will be developed to correlate/predict environmental effects on thermal and mechanical properties of the advanced composites. These models will aid in directing the materials development activities. The surface distortion of composite laminates/panels will be measured and modeled.

### **Milestones:**

- Establish contract task to develop low temperature Gr/Glass composites - March 1988.

- Develop capability to measure reflector panel distortions using laser holography - September 1988.

### **RTR 763-01-41-17 Coatings for Carbon-Carbon Composites**

#### **Objective:**

Develop oxidatively protected carbon-carbon material concepts to meet specific airframe and control surface requirements in support of Aero-space Plane.

#### **Approach:**

Evaluate in simulated NASP environments various promising oxidation-protection systems which were developed for propulsion applications. Build on these results, tailoring a new oxidation-protection system (in-depth oxidation protection, sealants, coatings) to meet specific NASP mission requirements.

#### **Milestones:**

- Preliminary evaluation tests completed on samples of oxidatively protected c-c in multiparameter environmental simulator - March 1988.
- Initiate multiparameter environmental simulation evaluations of candidate test materials - June 1988.
- Initiate dynamic environment (arc jet) testing of candidate test materials - June 1988.

### **Metallic Materials Branch**

Research in the Metallic Materials Branch for FY 88 will focus on advanced aluminum alloy technology for cryogenic tank applications, innovative metals processing and joining, and high temperature titanium aluminides and advanced metal-matrix composites for hypersonic vehicles. Plans for this research are outlined in figure 46. This research will be carried out under the following five RTR's:

### **RTR 505-63-01-02 Advanced Structural Metallics for Service to 1000°F**

#### **Objective:**

Develop a fundamental understanding of the metallurgical structure/mechanical property interactions resulting from powder processing, consolidation, and subsequent thermomechanical processing of intermediate and high temperature aluminum alloys prepared by advanced ingot and powder metallurgy techniques. Demonstrate the property and durability advantages of advanced aluminum alloys for aerospace structures. Develop advanced inorganic composite materials for aerospace structural applications.

Approach:

Prepare new aluminum alloy compositions of laboratory quantities by advanced I/M and P/M techniques. Develop and evaluate promising composite materials systems with light alloy metallic matrices and correlate microstructural/mechanical property relationships. Identify metallurgical characteristics controlling specific properties through laboratory analysis and development of optimized processing techniques to obtain tailored properties.

Milestones:

- Complete metallurgical characterization and initial consolidation of Al-Mn-Ca-Si alloy for high temperature applications - October 1987.
- Complete results of developed PM Al-Cu-Mg-Zr alloy in unreinforced and particulate reinforced product form - January 1988.
- Determine corrosion fatigue and stress corrosion cracking behavior of advanced aluminum alloys and light alloy matrix composites - March 1988.
- Produce PM aluminum alloy powders for high temperature applications using the LaRC gas atomization facility - April 1988.
- Fabricate, test, and evaluate SPF Al curved cap beaded web compression panels - May 1988.
- Develop processing to produce sheet material from aluminum alloy powder with Mn, Ca, and Si additions for high temperature applications - June 1988.
- Optimize chemistry and processing for enhanced superplasticity in advanced aluminum alloys - September 1988.

**RTR 505-63-01-03 Innovative Metals Processing for Airframe Structures**

Objective:

Develop improved aluminum alloys and innovative processing methods for fabricating lightweight aerospace vehicle structures. Develop advanced processing techniques for lightweight Al-Li and high temperature aluminum alloys and evacuated titanium honeycomb-core sandwich concepts.

Approach:

Combined in-house and contractual studies to define the potential of advanced aluminum alloys for airframe structural applications. Modify the composition of Al-Li alloys for enhanced superplasticity, weldability and post fabrication heat treatment. Explore the use of high temperature aluminum alloys and develop improved brazing and joining processes for fabricating evacuated titanium

honeycomb-core sandwich structure. Characterize material properties and design, fabricate and test structural elements.

Milestones:

- Characterize weldable Al-Li alloys - December 1987.
- Explore the use of high temperature aluminum alloys and joining technologies for airframe and tank applications - July 1988.
- Superplastically form small stiffened Al-Li structural segments - August 1988.
- Screen joining processes for fabricating coupon size evacuated titanium honeycomb-core sandwich concepts - September 1988.
- Determine the SPF characteristics of Al-Cu-Li-Zr-In alloy for aerospace structural applications - September 1988.

**RTR 506-43-71-01    Metallics for High Temperature Airframe Structures**

Objective:

Develop new high temperature metallics, processing and joining techniques, and coatings for environmental protection for use at temperatures from 500°F to 2000°F including in-situ and continuously reinforced advanced metal matrix composites and light alloy intermetallics.

Approach:

Combined in-house and contract research studies to develop and characterize advanced metallic systems produced by deposition techniques, rapid solidification rate technology and conventional high temperature processing. Establish suitable joining processes for very thin gage, lightly loaded structure. Demonstrate technology readiness through design, fabrication, testing, and evaluation of structural sub-components.

Milestones:

- Initiate study of dispersion strengthening mechanisms in in-situ reinforced aluminum alloys for >600°F applications - October 1987.
- Complete preliminary evaluation of titanium intermetallics and coating systems in hypersonic air environments - December 1987.
- Assess potential of oxide dispersion strengthened Ti-Mo alloys for high temperature applications - February 1988.
- Complete preliminary evaluation of the potential for designing nonequilibrium phases to improve high temperature properties and stability of RSR

intermetallics - April 1988.

- Determine high temperature properties of foil gage, ingot metallurgy titanium aluminide materials - June 1988.
- Evaluate very thin gage metallic substrates produced by deposition techniques - September 1988.

### **RTR 763-01-41-11 Advanced Processing of $Ti_xAl$ Composites for NASP**

#### **Objective:**

Develop advanced joining processes for fabricating  $Ti_xAl$  metal-matrix composite, RSR titanium honeycomb-core sandwich structure and develop an analytical model for predicting composite properties.

#### **Approach:**

Conduct in-house studies using available titanium based ingot metallurgy (IM) model materials to develop joining processes suitable for fabricating  $Ti_xAl$  composite sandwich structure. Screen candidate processes including brazing, liquid interface diffusion bonding, and diffusion bonding based on both metallurgical studies and mechanical property tests. Evaluate alternate LID material compositions to improve elevated temperature properties of IM  $Ti_3Al$ - $Ti_3Al$  joints. Develop an analytical model for predicting fatigue behavior and verify experimentally. Fabricate, test and evaluate small sandwich specimens and structural sub-elements using  $Ti_3Al$  composites as they become available.

#### **Milestones:**

- Determine the elevated temperature properties of LID bonded IM  $Ti_3Al$ - $Ti_3Al$  coupon joints - October 1987.
- Determine the RT face-face tension properties of LID bonded IM  $Ti_3Al$  face sheet titanium honeycomb-core sandwich specimens - December 1987.
- Develop LID compositions for improved elevated properties of LID bonded joints - June 1988.
- Demonstrate the use of melt overflow process for casting RSR titanium foil - August 1988.
- Develop and evaluate an analytical model for fatigue of MMC - September 1988.

## **RTR 763-01-41-14 Advanced Metal Matrix Composites**

### **Objective:**

Develop specific, high temperature metal matrix composites and associated fabrication technology for aero-space plane applications.

### **Approach:**

Establish surface treatments and/or coating systems for selected ceramic and organic fibers for optimum fiber/matrix stability. Fabricate and test minimum gage composite panels to establish performance limits. Develop techniques for structural component fabrication. Define scale-up requirements for large panel manufacture.

### **Milestones:**

- Unidirectional composites fabricated and evaluated - December 1987.
- Multi-layer, cross-ply composite panels fabricated - June 1988.

### **Concluding Remarks**

This document presents the FY 87 accomplishments, presentations and publications and the FY 88 research plans of the Materials Division.

# LANGLEY RESEARCH CENTER

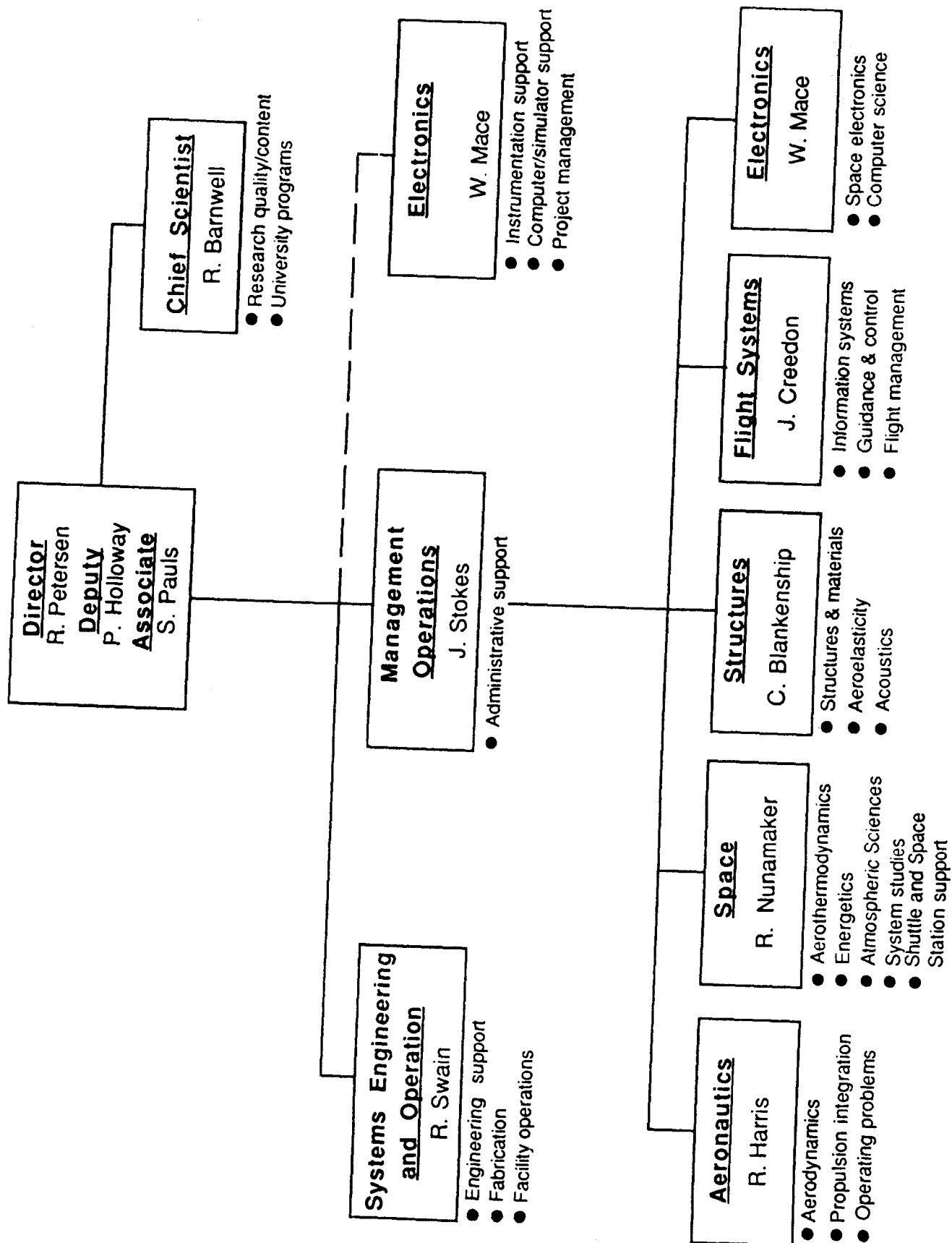


Figure 1.



# MATERIALS DIVISION

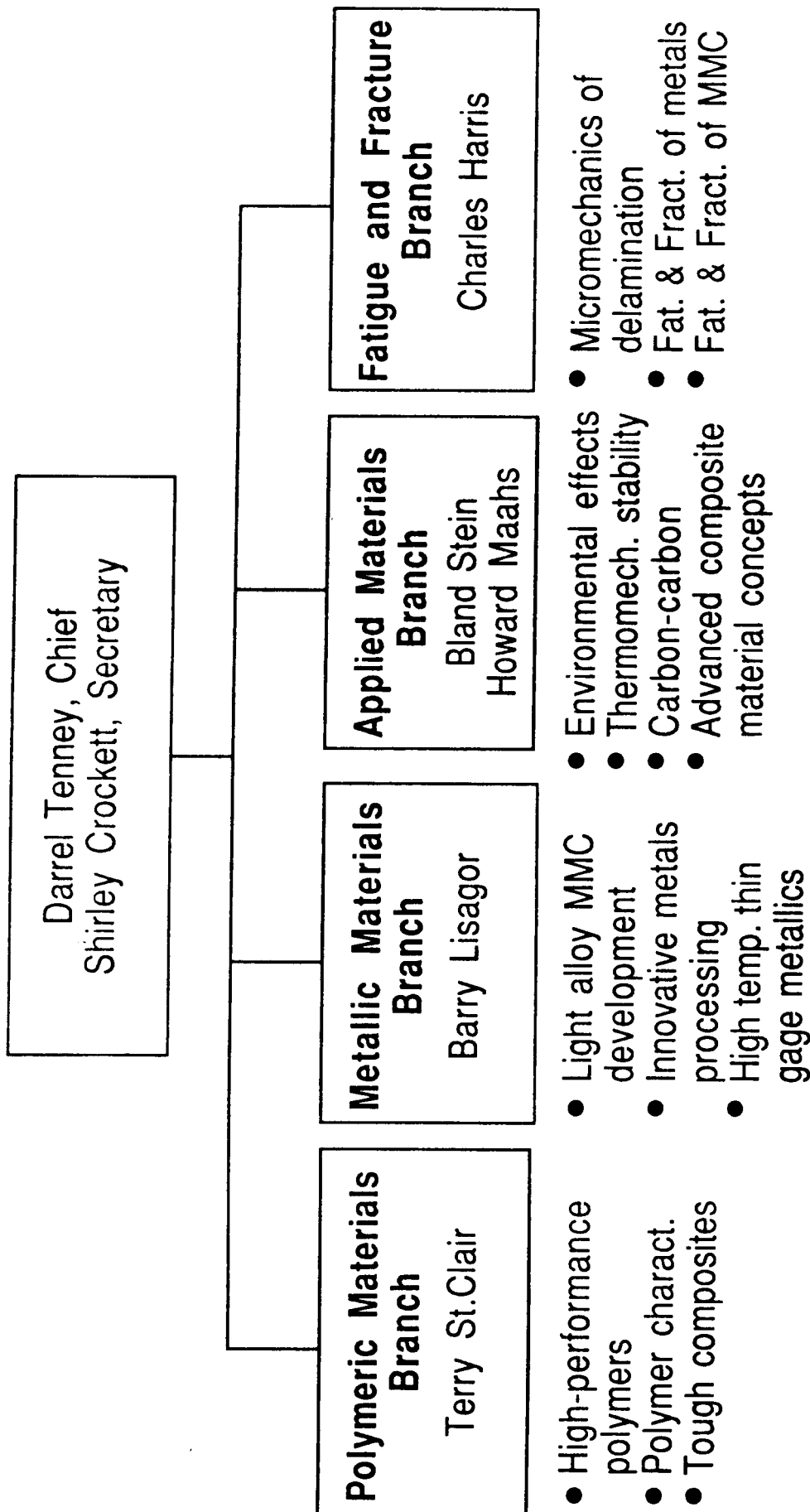
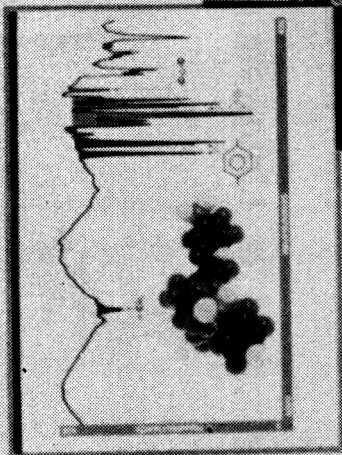
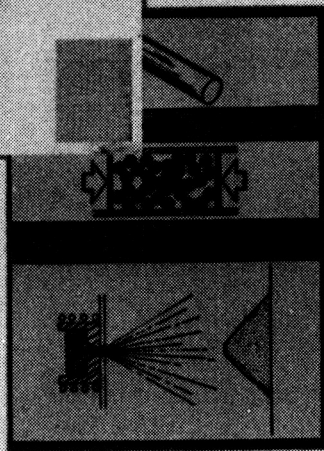


Figure 2.

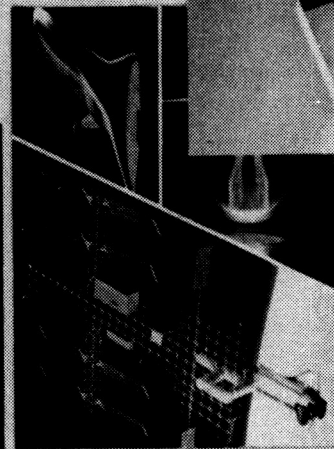


## METALS

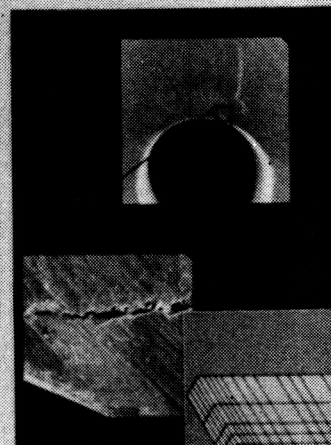
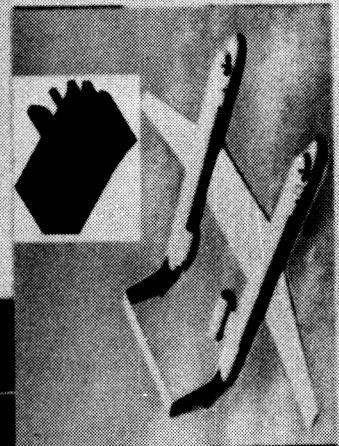


## POLYMERS

# MATERIALS RESEARCH



## APPLICATION



## FATIGUE AND FRACTURE

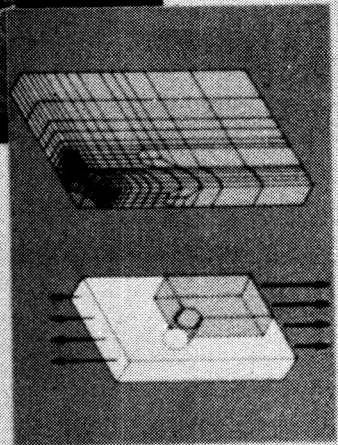


Figure 3.

## **MATERIALS DIVISION**

### **LONG RANGE THRUSTS - AERONAUTICS**

#### **Lead Role**

- o Metallic materials for aircraft structures
- o Carbon-carbon composites for hypersonic vehicles (Proposed)

#### **Support Role**

- o Composite materials for primary aircraft structures
- o Lightweight, hot structures for high-speed aircraft

## **MATERIALS DIVISION**

### **LONG RANGE THRUSTS - SPACE**

#### **Lead Role**

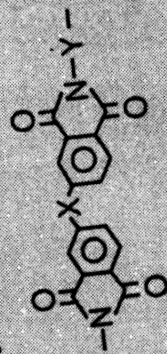
- o Materials durability in the space environment

#### **Support Role**

- o Aerothermal structures and materials technology for Advanced Launch Systems
- o Structures, materials, and dynamics technology for Space Station

# POLYMERIC MATERIALS

Novel synthesis



Matrix resins    Adhesives    Films

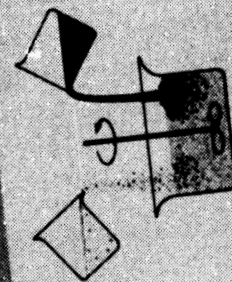
Advanced characterization



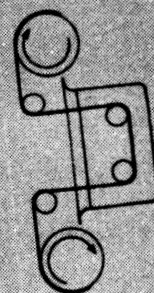
Chemical, physical & mechanical

Structure  
property  
relationships

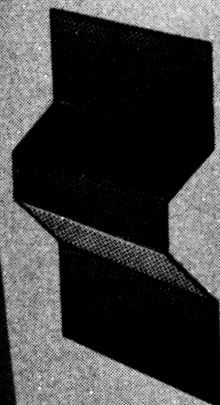
Composite development



Resin development



Fiber impregnation



Composite processing

Figure 5.



POLYMERIC MATERIALS BRANCH  
FIVE YEAR PLAN

MAJOR THRUST	FY87	FY88	FY89	FY90	FY91	EXPECTED RESULTS
High performance polymer concepts						New polymers and polymer technology
Composite matrices						Improved understanding of high performance materials
Composite processing and adhesive bonding						Balanced composite properties
						Advanced processing and bonding technology for high performance materials

Figure 6.

## POLYMER TECHNOLOGY TRANSFER

Terry L. St. Clair  
Polymeric Materials Branch  
Ext. 3041      October 1986  
RTOP 506-43-11

**Research Objective:** To assure the widest use and greatest benefit from NASA-developed polymer transfer.

**Approach:** Over the past decade much novel polymer technology has been developed at LaRC in the high temperature/advanced resin area in support of U.S. aerospace activities. Developments by U.S. industry are limited in these areas because immediate applications or an established market are lacking. Patents are obtained by NASA on new polymer systems. These patents can then be licensed to companies interested in commercializing the materials. A special effort is being made to keep U.S. industry aware of recent NASA developments in advanced polymers.

**Accomplishments:** After an induction period as research capabilities were being formed, the polymer technology that has been developed in the Materials Division is beginning to be exploited in the industrial sector. The chart details some technology transfers that have occurred over the past few years. Several of these developments such as the LARC-160 and LARC-TPI are commercially available today. In other cases, such as the polyimidesulfone and the polyphenylquinoxaline, developmental quantities are being made. The other technologies such as the polyimide laminating and metal ions in polyimides are also beginning to come to the market in prototype forms. These will develop with time.

**Significance:** Langley-developed polymer technology is being put into commercial practice by industry. Because most of these materials are covered by NASA patents, industry is willing to invest the resources required to bring them to commercial production because their position can be protected through licensing agreements. Polymers that were originally developed with particular aerospace applications in mind are finding broader applications because of their commercial availability.

**Future Plans:** Continued research activities will be carried out on advanced polymer systems and invention disclosures will be filed. Close interactions with industry will continue in order to assure the widest possible use of NASA's technology.

Figure 7(a).

# NASA POLYMER TECHNOLOGY TRANSFER

SYSTEM	DEVELOPED	PATENTED	LICENSEE	CONSIDERATION TO NASA
LARC-160	Mid 1970's	1979 & 1980	U.S. Polymeric, Fiberite, Hexcel, American Cyanamid, King Mar	None
LARC-TPI	Mid to late 1970's	1977 & 1978	Mitsui Toatsu, Rogers, High Tech Services	\$8000 * + percentage
Polyimide-Sulfone	Early 1980's	1983 & 1984	M&T Chemical, Celanese	\$8000 * + percentage
Polyimide Laminating Technology	Late 1970's	1985	Rogers (Exclusive)	\$5000 ** + percentage
Polyimide/Palladium	Early 1980's	1981	Rogers (Exclusive)	\$5000 ** + percentage
Polyimide/Aluminum Ions	Early 1980's	1981	Mitsui Toatsu, High Tech Services	\$2000 ** + percentage
Elastomer Toughened Polyimides	Late 1970's	1983 & 1985	High Tech Services	\$4000 *** + percentage
Polyphenyl-Quinoxalines	1960's	None	Hunt Chemical	None

\* Four NASA Patents

\*\* One NASA Patent

\*\*\*Two NASA Patents

Figure 7(b).



## **.PREPARATION OF AMIDE-IMIDE POLYMERS**

James F. Dezem  
Polymeric Materials Branch  
Ext. 3041      December 1986  
RTOP 506-43-11

**Research Objective:** To prepare and characterize thermally-stable, tough polyimides incorporating amide linkage for potential advanced applications as coatings, adhesives and composite matrix resins.

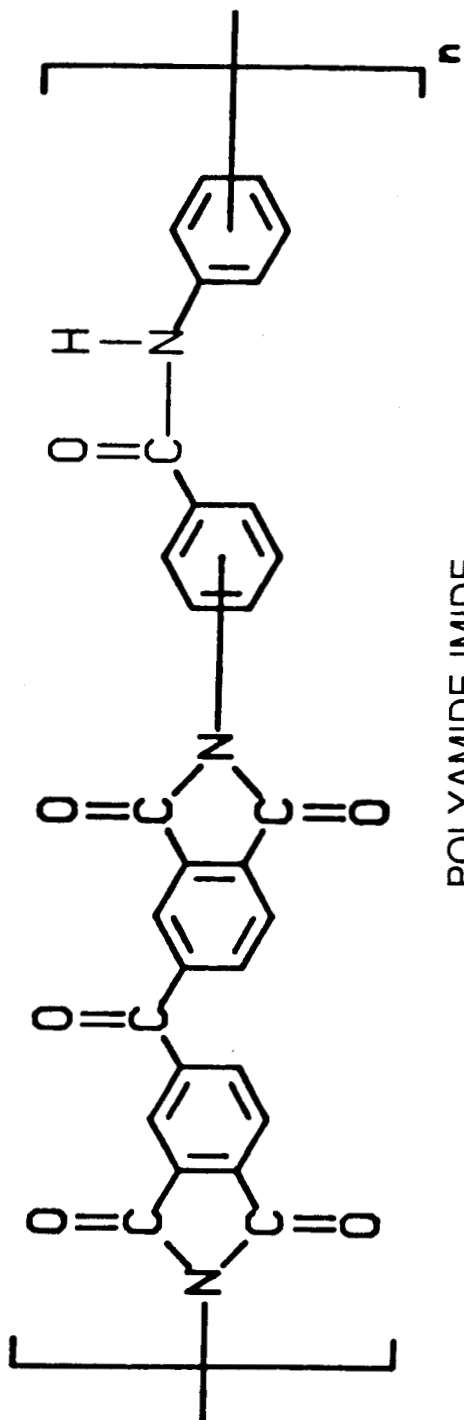
**Approach:** Prepare a series of novel amide-imide polymers and evaluate physical and mechanical properties.

**Accomplishments:** Four polyimides were prepared from novel amide diamines. The structure, shown in the accompanying figure, differs from that of LARC-TPI by the incorporation of a more flexible amide linkage. These polyamide-imides exhibited high inherent viscosities and glass transition temperatures. They were made into tough, flexible films which showed good thermal stability and good resistance to organic solvents. Mechanical properties of the films (see figure) were better than those of LARC-TPI, especially the 4,4'-isomer. Its exceptionally high modulus (1068 ksi) value makes this material extremely attractive for composite applications. Films of the 4,4'-isomer also exhibited tough behavior during impact evaluation.

**Significance:** These polyamide-imides may be useful as high-temperature films and coatings and the 4,4'-isomer system should exhibit some highly sought-after properties as a matrix resin in graphite-reinforced structure.

**Future Plans:** Evaluation of the adhesive properties of these polyamide-imides is planned for the future. The ability to spin fiber from these polymers will also be evaluated. Quantitative measurements will be made on polymer moldings to determine toughness. A scale-up of the resin will be made and composites fabricated and evaluated.

**Figure 8(a).**



Polyimide	Properties				
	Inherent Viscosity	Tg(C)	Tensile Str. (Ksi)	Yield Str. (Ksi)	Tensile Modulus (Ksi)
3,3" - DABA/BTDA	0.93	283	14.1	8.8	476
4,4" - DABA/BTDA	1.26	-	26.1	14.3	1068
3,4" - DABA/BTDA	0.82	310	18.4	9.5	555
4,3" - DABA/BTDA	0.95	313	17.1	9.0	501
LaRC-TPI	0.91	236	16.5	11.1	464

Figure 8(b).

## CRYSTALLIZATION IN THERMOPLASTIC RESINS - LARC-TPI

Noel T. Wakelyn  
Polymeric Materials Branch  
Ext. 3041 August 1987  
RTOP 506-43-11

**Research Objective:** To develop an understanding of crystallinity in thermoplastic polymers and learn how to exploit it in polyimides such as LARC-TPI. High levels of crystallinity generally tend to improve processing characteristics. Semi-crystalline polymers, also, have higher moduli and are more solvent resistant than their amorphous counterparts.

**Approach:** Samples of LARC-TPI, a semi-crystalline thermoplastic resin, were synthesized by different procedures, and, in one case, subjected to an annealing treatment. They were then analyzed using wide angle x-ray scattering (WAXS) techniques to provide a better understanding of the crystalline forms of this material.

**Accomplishments:** Comparative x-ray diffractograms of LARC-TPI powder are shown on the accompanying figure (the intensity of the y-axes for each curve has been shifted for super position). This complex imide structure, which had previously been thought to exist only in the amorphous form (bottom curve), is shown to be capable of crystallizing in at least three different forms. The diffractogram of the commercial powder shows one crystalline form. The material in the upper curve was produced by a different synthetic route developed at LaRC. This sample exhibits a higher degree and slightly different type of crystallinity than the commercial sample. Either of these crystalline materials may be annealed at 301°C, slightly above their melting point, to produce the third crystalline form shown in the figure. This is the thermodynamically stable form of the polymer. Further heating to 350°C destroys all crystallinity and affords an amorphous polymer.

**Significance:** The data on the semi-crystalline commercial LARC-TPI has been correlated with rheological data on melts of this same crystalline form to help in the understanding of how crystalline melts affect viscosity/processability of polymers. To date this novel crystallinity in LARC-TPI has allowed us to prepare well consolidated graphite-reinforced composites. X-ray diffractograms have proven invaluable in helping to define the level of crystallinity in the LARC-TPI composites and neat resin moldings.

**Future Plans:** Rheological data will be generated on the new crystalline form of LARC-TPI that was prepared at LaRC and will be compared to existing data on the commercial form. Composites prepared from the LaRC form will be compared with existing data on composites from the commercial polymer.

Figure 9(a).

COMPARED DIFFRACTOGRAMS FOR DIFFERENT  
CRYSTAL FORMS OF LARC-TPI

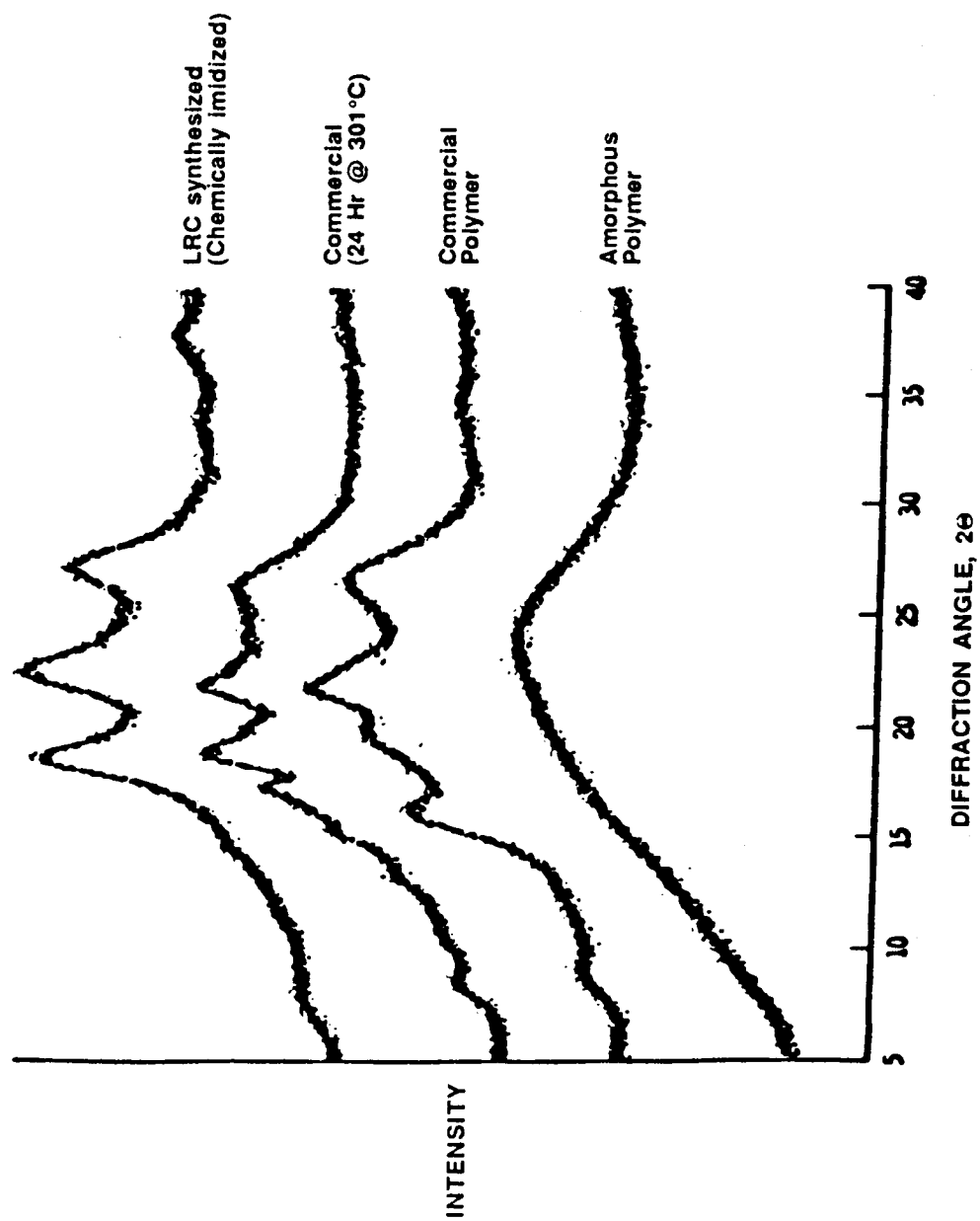


Figure 9(b).

## LARC-TPI COMPOSITES VIA NEW SLURRY PROCESS

Norman J. Johnston, Robert M. Baucom and Terry L. St. Clair  
Polymeric Materials Branch  
Ext. 3044 February 1987  
RTOP 505-63-01

**Research Objective:** To improve the flow properties of thermoplastic polyimides in order to use them as matrices for high performance composites.

**Approach:** Standard high molecular weight polyimides have melt viscosities so high they are difficult to process. By adding to these materials a low molecular weight semicrystalline polyimide powder that has a very low melt viscosity, a polymer blend is obtained whose melt flow properties are greatly enhanced.

**Accomplishments:** Insoluble LARC-TPI semicrystalline polyimide powder was added in varying percentages to LARC-TPI polyamide-acid diglyme solution, creating a stable slurry used to prepreg onto carbon fiber. The insoluble 2-4 micron particles nicely penetrated the 12,000 filament tow and were evenly distributed on the fiber, the polyamide-acid solution acting as a binder (see SEM).

Melt flow of the polymer blend varied with the percent powder as the chart shows and flow enhancement up to five times that of the virgin polyimide without powder was observed. Standard thermoplastic molding procedures (650°F/300 psi/1 hr) were employed to fabricate void-free well-consolidated composites whose short beam shear and flexure strengths at room temperature were extremely high and were 66 and 100 percent higher, respectively, than those of composites made without the semicrystalline powder. Flexure strengths at 350°F were also improved 100 percent.

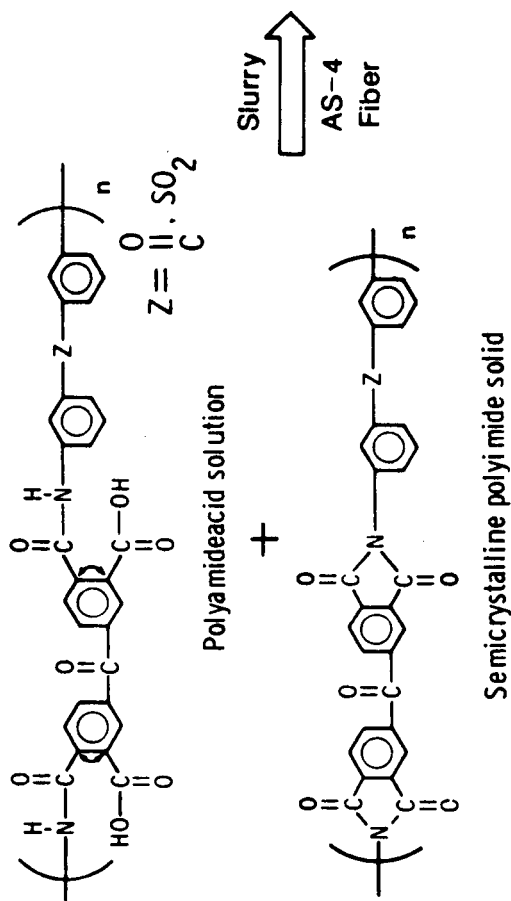
**Significance:** LARC-TPI and polyimidesulfone (PISO<sub>2</sub>) compositions doped with semicrystalline polyimide powders are excellent candidate matrices for high performance composites applications such as ATF, high speed commercial transports, and rocket components.

**Future Plans:** Blends of other polyimide compositions such as Langley's PISO<sub>2</sub> with LARC-TPI and other semicrystalline powders are being studied. Engineering properties of LARC-TPI and PISO<sub>2</sub> graphite composites and neat resin moldings are being obtained. Thermoforming and filament winding studies are underway.

Figure 10(a).

# LARC-TPI COMPOSITES VIA NEW SLURRY PROCESS

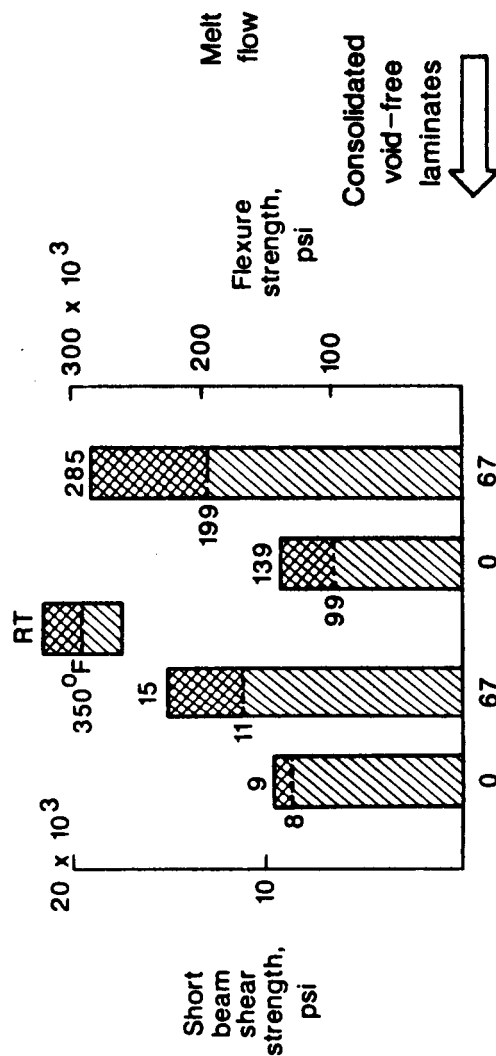
## CHEMISTRY



Semicrystalline polyimide solid

## LARC-TPI

## COMPOSITE MECHANICAL PROPERTIES



% LARC-TPI Semicrystalline powder

Figure 10(b).

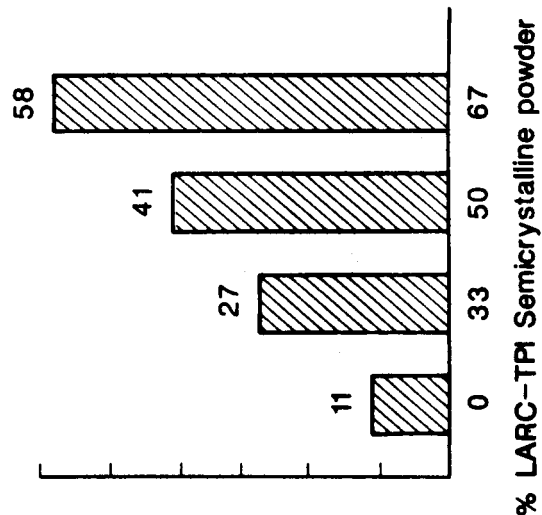
## PREPREG SEM



2000 X



## ENHANCED MELT FLOW



% LARC-TPI Semicrystalline powder

This page intentionally left blank.

## THE EFFECT OF DIAMIC ACID ADDITIVES ON THE PROCESSABILITY OF POLYIMIDES

Diane M. Stoakley, Harold D. Burks and J. Richard Pratt  
Polymeric Materials Branch  
Ext. 3041 June 1987  
RTOP 506-43-11

**Research Objective:** Conventional polyimides are tough, flexible, thermooxidatively stable and solvent resistant, but they are very difficult to process. LARC-TPI and 422 are polyimides developed at NASA-Langley that possess somewhat improved processability; however, further improvements are necessary to expand their use as high performance matrix resins. The current research was focused on improving the melt viscosity of polyimide resins by incorporation of diamic acid additives.

**Approach:** Compatible low molecular weight diamic acid additives were synthesized and added at varying concentrations to the polyamic acid resins of LARC-TPI and 422. The effect of incorporating these additives on the processability of LARC-TPI was determined by characterizing polymer films with thermal mechanical analysis, while the effect on 422 was determined by evaluating films and the melt flow properties of molding powders in a capillary rheometer.

**Accomplishments:** The apparent viscosity of the 422 control was lowered by an order of magnitude with the use of 2.5% of selected additives. This decrease in melt viscosity was accomplished with only a slight decrease in glass transition temperature. When composites were prepared from the TPI system containing a diamic acid additive the increased flow resulted in better consolidation which translated into improved room temperature and elevated temperature mechanical properties.

**Significance:** The incorporation of diamic acid additives into polyimides results in a significant decrease in melt flow properties extending their use as processable matrix resins.

**Future Plans:** This approach to improving resin processability is being evaluated and further developed by a variety of aerospace material suppliers and users.

Figure 11(a).



# APPARENT VISCOSITIES OF 422 COPOLYIMIDE WITH ADDITIVES

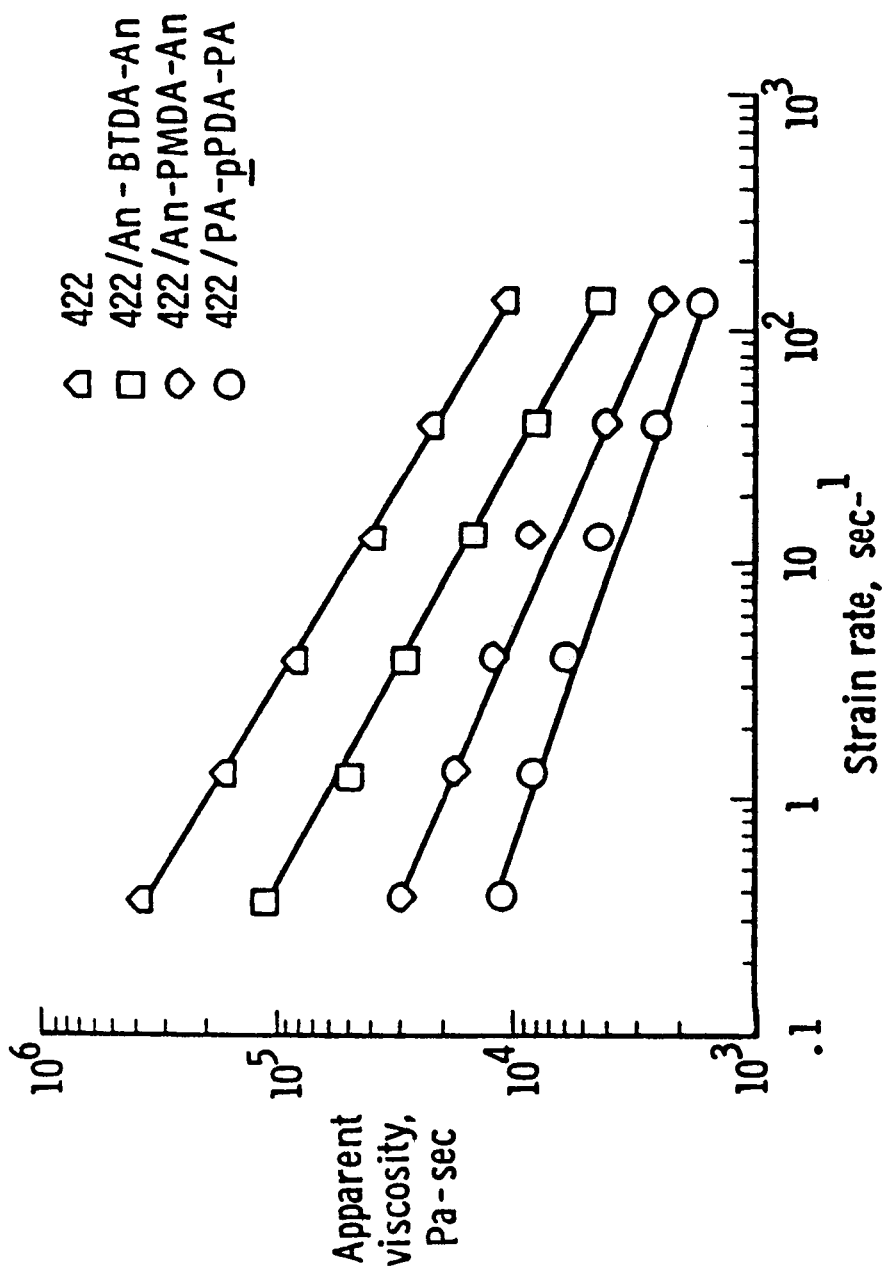


Figure 11(b).

# COMPOSITE MECHANICAL PROPERTIES

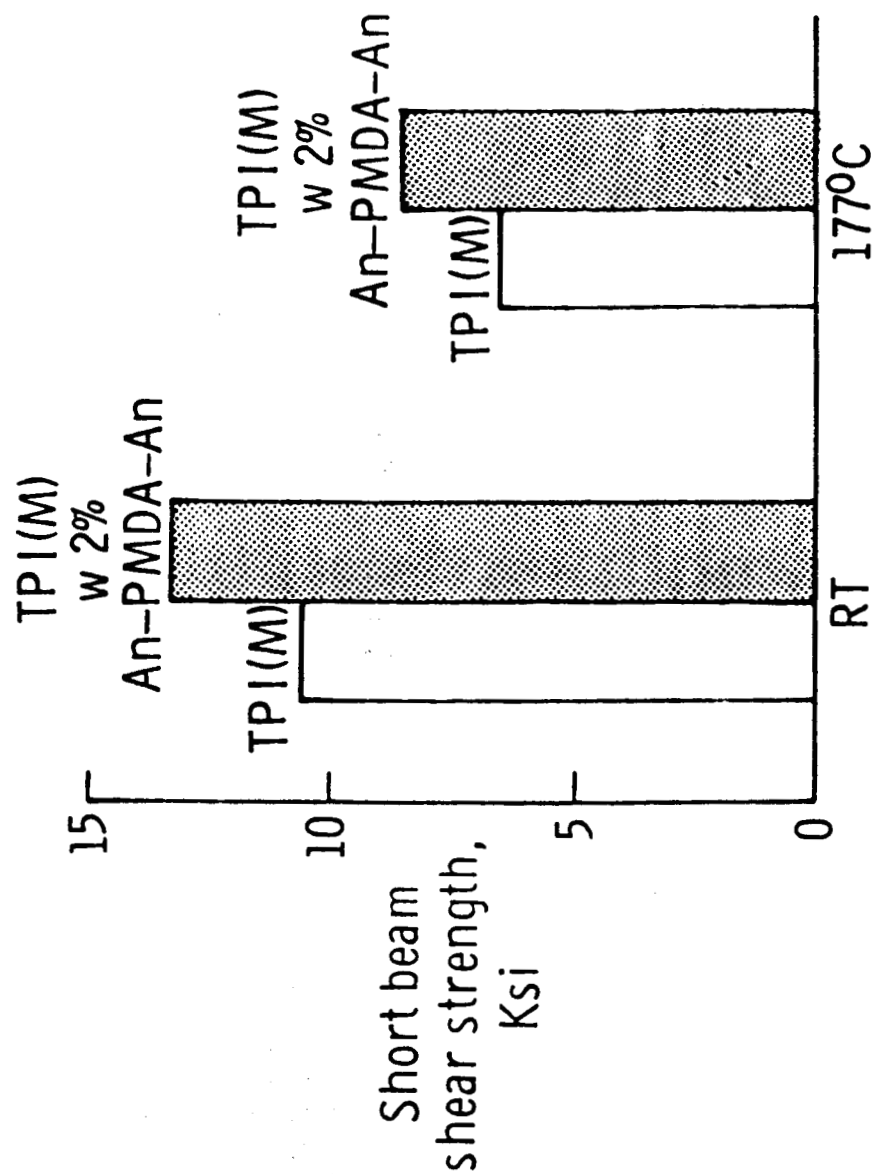
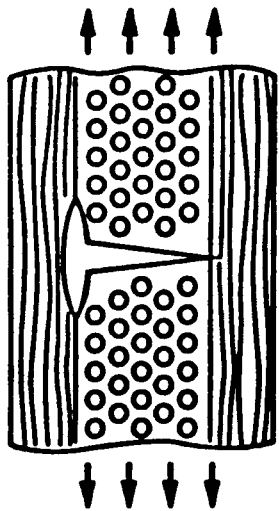
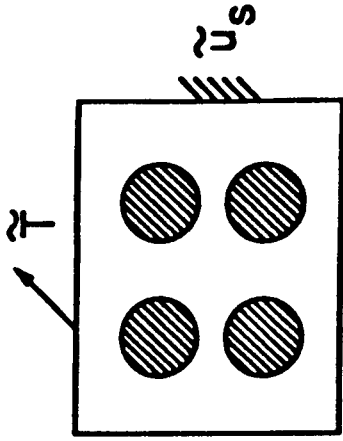


Figure 11(c).

Composite Damage  
Mechanics



Micromechanics



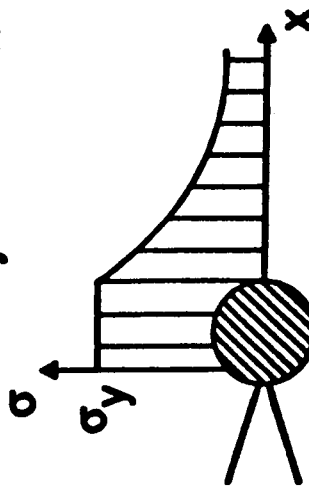
Polymeric  
Composites

Metal Matrix  
Composites

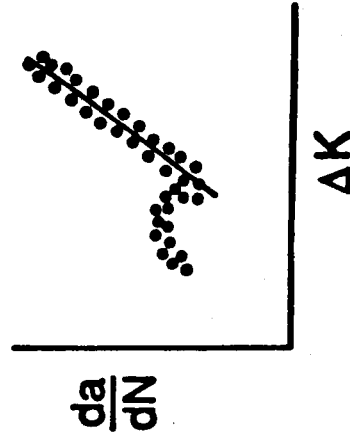
## MECHANICS OF MATERIALS

- Inelastic constitutive behavior
- (Strength) Failure criteria
- Life prediction methodology

Stress analysis of cracks



Fatigue crack growth



Metallic Alloys

Figure 12.

FATIGUE AND FRACTURE BRANCH  
FIVE YEAR PLAN

MAJOR THRUST	FY87	FY88	FY89	FY90	FY91	EXPECTED RESULTS
Metals and metal matrix composites		Short crack growth				Strength and life prediction methodology
		3-D crack closure				
		Life prediction methods				
		Metal matrix failure mechanisms				
Composites						Fatigue and fracture technology  Guidelines for constituent property requirements
		Delamination studies				
		Thick laminate fracture				
		Advanced composite forms				
		Failure micromechanics				
Computational methodology						Efficient tools for computational fracture mechanics analyses
		Fatigue testing				
		Material & geometric nonlinearities				
		Elastic singularity problems				
		Advanced numerical methods				
		Viscoelastic analyses				

Figure 13.

## FATIGUE LIFE OF MATERIAL WITH A MACHINING SCRATCH

R. A. Everett, Jr.  
Fatigue and Fracture Branch  
Ext. 2715 November 1986  
RTOP 505-63-01

**Research Objective:** To determine the effects of a machining scratch on the fatigue life of a high strength steel typical of those used in dynamic parts of helicopters.

**Approach:** Constant amplitude fatigue tests were run on unnotched specimens with and without a 0.002 in. deep machining scratch that could pass quality control inspections. The data were compared to determine the effects of the machining scratch on the material endurance limit. Specimens with scratches that had been shot peened were also tested to see if the compressive residual stresses from the shot peening would provide any relief from the stress concentration caused by a scratch.

**Accomplishment:** The figure shows fatigue life in cycles for several alternating stress levels,  $S_a$ . The machining scratch caused about a 40% reduction in the material's endurance limit. The tests on the specimens that had been shot peened showed that the compressive residual stresses produced by the shot peening almost eliminated the effects of the stress concentration caused by the scratch.

**Significance:** These tests have shown that a scratch can significantly reduce the fatigue strength of a high strength steel. The test results have also shown that shot peening can negate the effects of small stress concentrations.

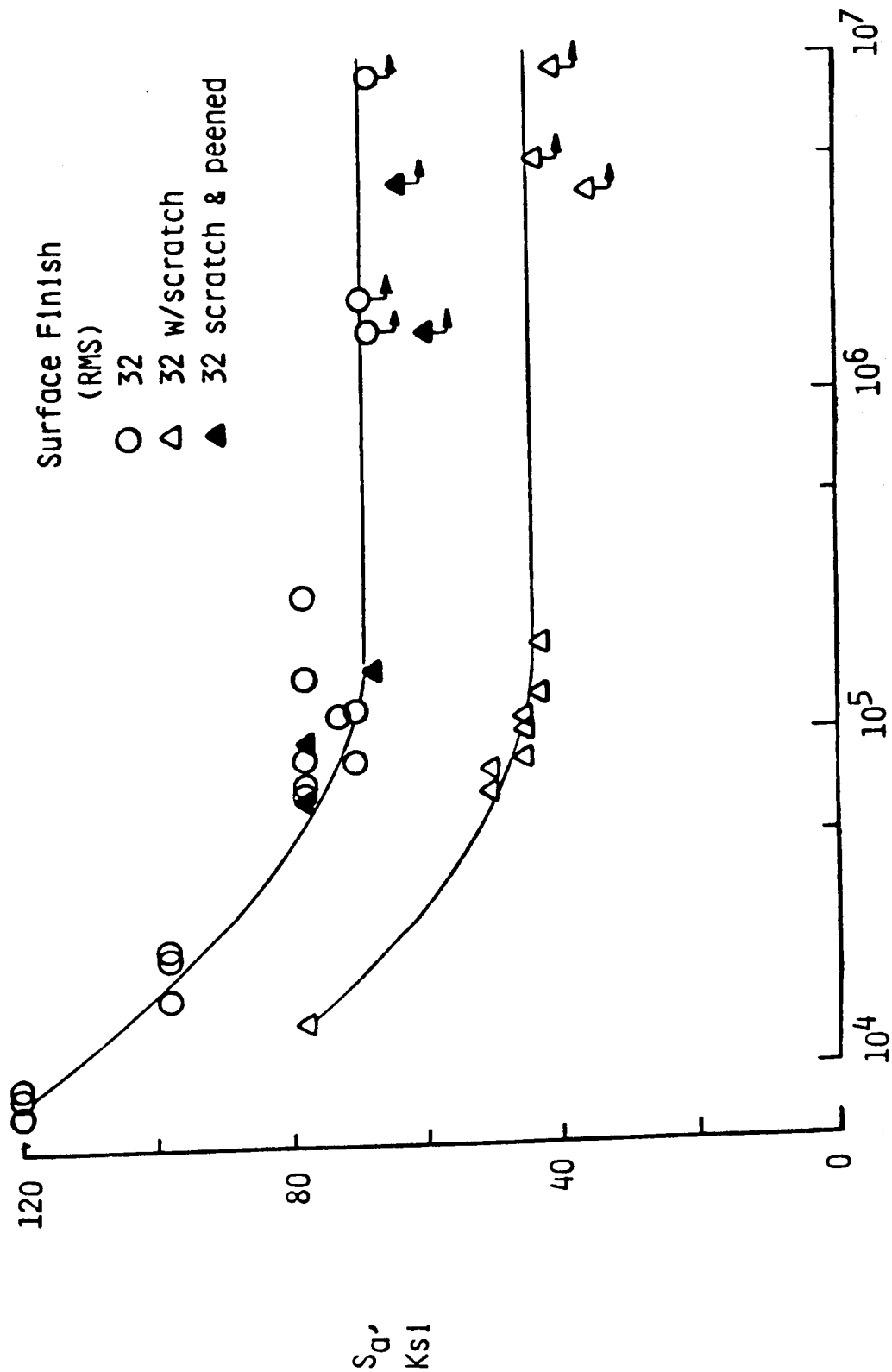
**Future Plans:** This work is generically related to the "small crack" effects in fracture mechanics. A program is currently being planned for a study of the "small crack" effect on high strength steels.

**Figure 14(a).**

# STRESS VS. CYCLES TO FAILURE FOR 4340 STEEL

$F_{tu} = 210 \text{ Ksi}$

$R = -1$



N, cycles  
Figure 14(b).

## THREE-DIMENSIONAL ANALYSIS OF FATIGUE CRACK CLOSURE

R. G. Chermahini, K. N. Shivakumar, and J. C. Newman, Jr.  
Fatigue and Fracture Branch  
Ext. 3192 March 1987  
RTOP 505-63-01

**Research Objective:** To develop an analytical model to calculate plasticity-induced fatigue crack closure along the crack front in finite thickness bodies.

**Approach:** A three-dimensional, elastic-plastic, finite-element analysis code has been written to subject FEM models to cyclic loads and to simulate fatigue crack growth by extending the crack by one element at the maximum applied stress ( $S_{max}$ ) in each cycle. As the model is loaded/unloaded, the code computes the crack-surface contact stresses that are caused by residual plastic deformations left behind the advancing crack. The progression of crack opening/closing along the crack front is determined by tracking the loads at which the contact stresses became zero/nonzero.

**Accomplishment:** A model of a finite-thickness (B) plate with a through-thickness crack of initial length "C" was subjected to a constant-amplitude loading at a stress ratio ( $S_{min}/S_{max}$ ) of 0.1. The figure shows the calculated progression of the opening/closing profiles on the crack surface during the loading portion of a cycle. The shaded region indicates areas where the crack is closed. At a stress of 0.1  $S_{max}$ , the crack is closed at the crack tip along the entire crack front. At 0.36  $S_{max}$ , the interior is fully open but the exterior layers are still closed. For stress levels greater than 0.56  $S_{max}$ , the entire crack was open. This sequence was reversed upon unloading.

**Significance:** Knowledge of the crack closure behavior along the entire crack front will significantly improve the understanding of crack growth processes in thick plates. Current experimental techniques for measuring crack closure provide a single "averaged" result for the entire crack front.

**Future Plans:** The analysis code will be used to perform a parametric study of loading and finite-thickness parameters that may affect crack closure behavior.

Figure 15(a).

# 3-D ANALYSIS OF FATIGUE CRACK CLOSURE BEHAVIOR

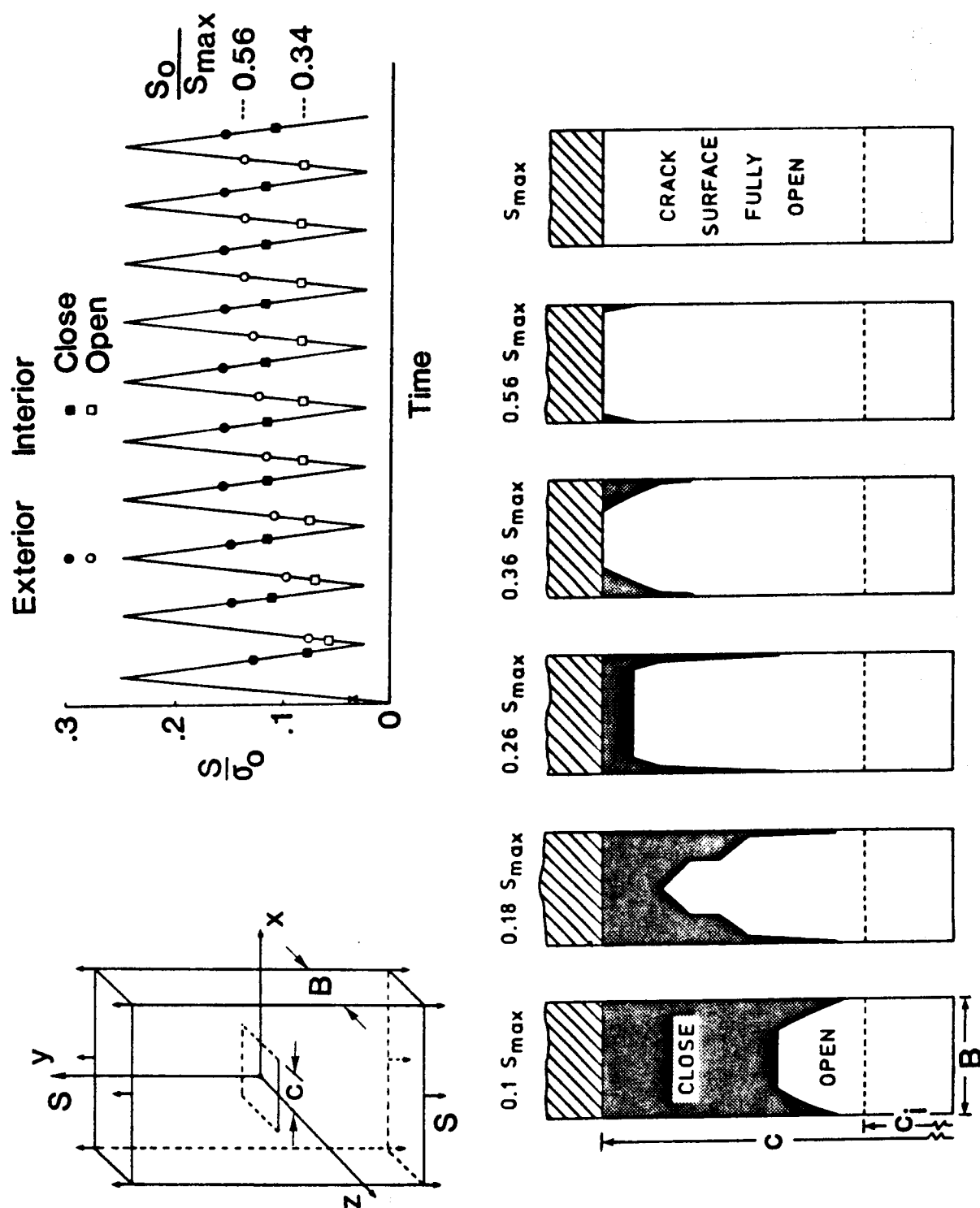


Figure 15(b).



# FIBER-MATRIX SEPARATION IN SILICON CARBIDE/TITANIUM MATRIX COMPOSITES

W. S. Johnson, S. J. Lubowinski, A. L. Highsmith, and C. A. Hoogstraten  
Fatigue and Fracture Branch  
Ext. 2715 September 1987  
RTOP 505-63-01

**Research Objective:** To determine elastic properties and identify failure modes in titanium matrix composites.

**Approach:** The material system studied in this investigation consisted of a titanium (Ti 15-3-3-3) matrix reinforced by continuous silicon carbide (SCS6) fibers. Room temperature quasi-static tension tests were performed on matrix material, and on [0]8, [90]8, [0/90]2s, [0/±45/90]s, and [02/±45]s composite laminates in order to evaluate an existing elastic-plastic model which had successfully predicted the response of other metal matrix systems. Initial moduli and Poisson's ratios were in good agreement with those predicted by the model. However, the laminates containing off-axis plies exhibited non-linear mechanical response at stress levels which were significantly lower than the onset of yielding predicted by the model. The edge replication technique was used to document damage development in the laminates. In the edge replication technique, a permanent impression of the specimen edge is produced in a cellulose acetate film. Edge replicas were taken at various stages of the quasi-static load history of a specimen, and were subsequently examined via scanning electron microscopy.

**Accomplishment:** It was found that after sufficient load was applied to specimens containing off-axis plies, fibers began to separate from the matrix material. Upon unloading, the fiber and matrix were again in contact. The figure shows a representative stress-strain curve for a [0/90]2s laminate which was reloaded after fiber-matrix separation had occurred. The micrograph at the left shows the fiber and matrix in contact at low stress, while the micrograph at the right shows evidence of separation at high stress. More detailed evaluation revealed that the separations occur primarily in the reaction zone between the silicon in the fiber and the titanium in the matrix. The "knee" in the stress-strain curve is indicative of the loss of stiffness that occurs when fibers in off-axis plies are no longer in contact with the matrix, and therefore no longer carry load.

**Significance:** The results of this study indicate that the fiber-matrix interface in the silicon carbide/titanium system is quite weak. Improved bonding between fiber and matrix is needed in order to raise the operating stress level of this material to a desired level.

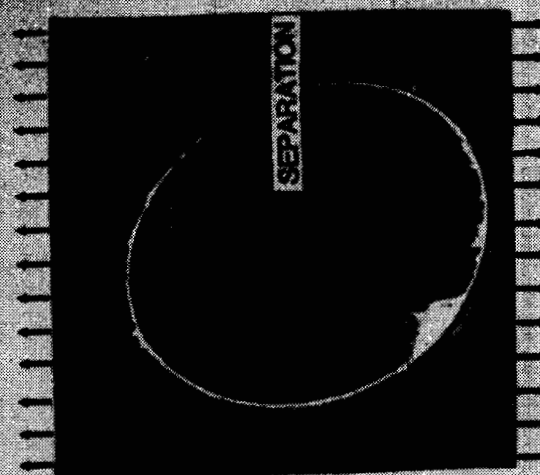
**Future Plans:** We are currently planning both fatigue and fracture tests on the mentioned laminates to further evaluate failure modes and processes.

Figure 16(a).

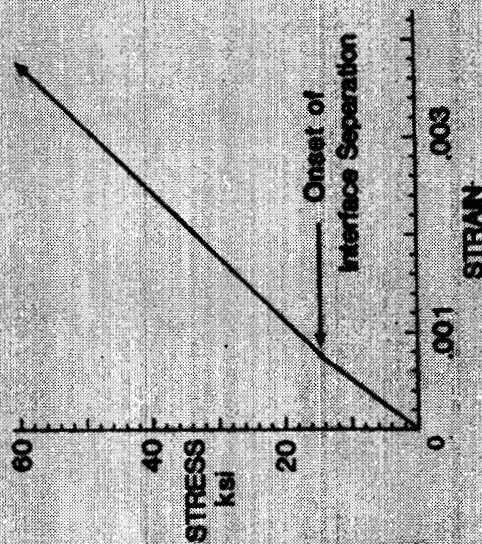
# FIBER/MATRIX INTERFACE FAILURE

SCS<sub>6</sub>/Ti-15-3

[0/90/0/90]<sub>s</sub>



60 KSI



UNLOADED

Figure 16(b).

## DELAMINATION FATIGUE BEHAVIOR OF COMPOSITE MATERIALS

T. Kevin O'Brien  
Fatigue and Fracture Branch  
Ext. 2093 January 1987  
RTOP 506-43-11

**Research Objective:** To develop a methodology for quantifying the improvement in delamination fatigue life gained from a toughened matrix.

**Approach:** Graphite reinforced composites often delaminate under repeated loading as a result of interlaminar stresses. Recently, composite materials with toughened matrix resins have been developed to improve the inherent delamination resistance. Edge delamination fatigue tests were conducted on graphite reinforced composites with a variety of matrices ranging from very brittle to very tough. The number of cycles to delamination onset was recorded at several maximum cyclic strain levels. The maximum cyclic strain was substituted into a closed-form equation for the strain energy release rate  $G$ . The maximum cyclic  $G$  was then plotted versus the cycles to delamination onset. The cycles to delamination onset were presented as a function of  $G$  to obtain a generic representation of the material behavior that is independent of layup and ply thickness.

**Accomplishment:** The figure shows the number of constant-amplitude, tension load cycles required to form an edge delamination in the 0/90 interface of (35/-35/0/90)<sub>s</sub> laminates as a function of the critical strain energy release rate,  $G_c^M$ . Data are shown for four graphite reinforced composites whose matrices have varying degrees of toughness. The matrix materials were (1) Narmco 5208, a 350°F brittle epoxy, (2) Hexcel H205, a 250°F epoxy, (3) Cyanamid HST7, a 350°F epoxy with a tough adhesive interleaf between each ply, and (4) ICI Polyetheretherketone (PEEK), a semicrystalline thermoplastic. As the figure indicates, there is a large difference in the static interlaminar fracture toughnesses of these materials shown on the ordinate at  $N=1$ , but the cyclic strain energy release rate endurance limits at  $10^6$  cycles did not differ greatly.

**Significance:** This study indicates that toughened resins produced only small improvements in delamination durability. Therefore, structural behavior that depends primarily on the static interlaminar toughness may be improved for a toughened matrix composite; however, structural performance in fatigue, such as delamination around an open hole, may not be significantly improved.

**Future Plans:** The influence of residual thermal stresses on the delamination fatigue of composites will be investigated.

Figure 17(a).

# DELAMINATION FATIGUE BEHAVIOR OF COMPOSITE MATERIALS

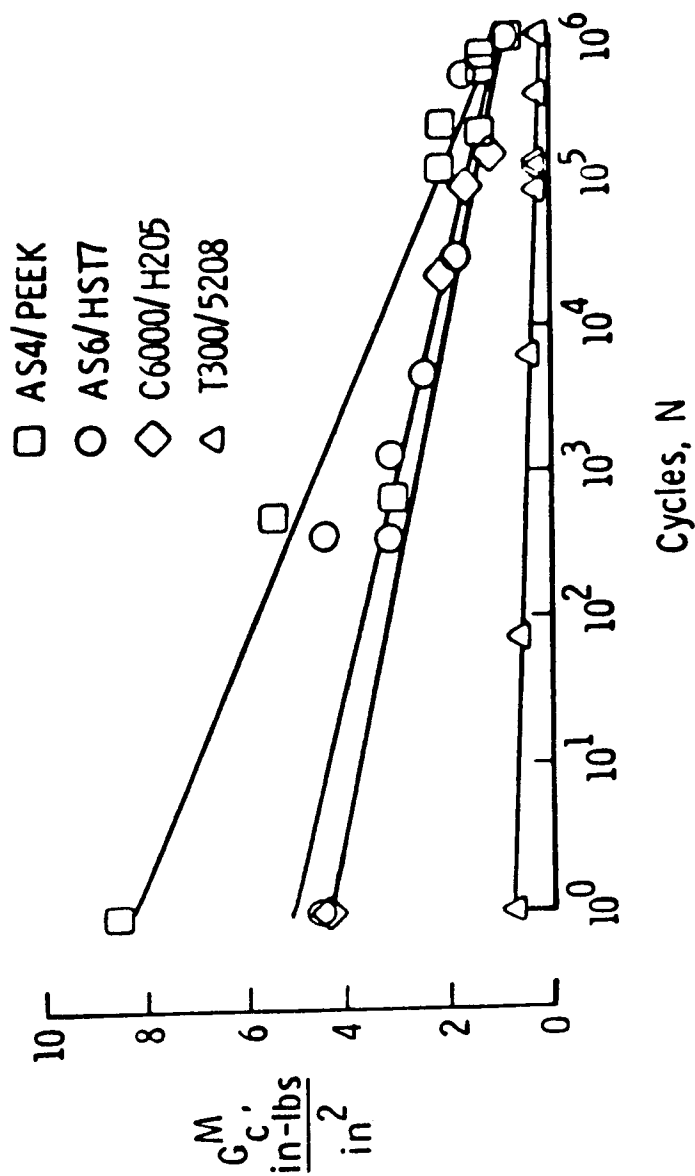


Figure 17(b).

## MATRIX YIELDING AT A DELAMINATION FRONT

John H. Crews, Jr., K. N. Shivakumar, and I. S. Raju  
Fatigue and Fracture Branch  
Ext. 3048 July 1987  
RTOP 505-63-01

**Research Objective:** To analyze the influence of bond thickness on yielding at a delamination front.

**Approach:** A finite-element model was developed to represent a double cantilever beam (DCB) specimen that is widely used to measure delamination toughness. This DCB specimen consisted of two graphite/epoxy laminates bonded together by an epoxy adhesive layer of thickness  $t$ , as shown in the first figure. The finite-element model was loaded to simulate an insipient growth condition at the delamination front, and elastic stresses were calculated for the adhesive layer near the delamination. These stresses were then used with the von Mises yield condition to estimate the delamination-tip yield zone. This procedure was repeated for a range of adhesive layer thicknesses.

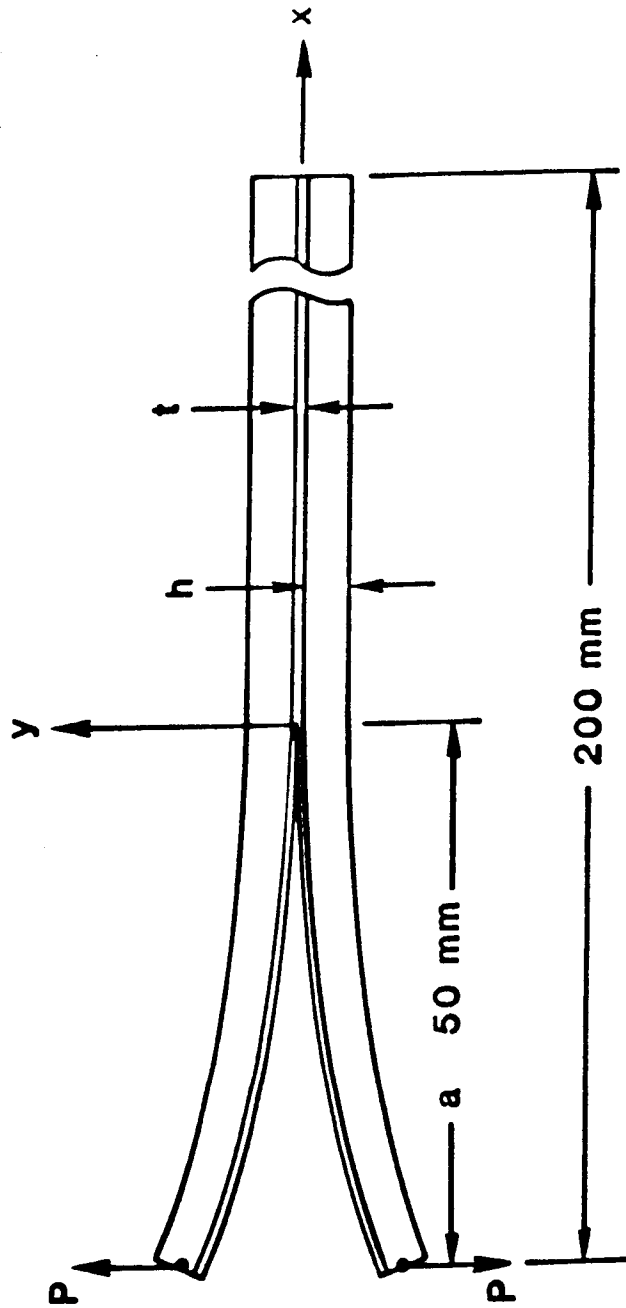
**Accomplishment:** The estimated yield zones are shown in the next figure. The smallest adhesive layer thickness ( $t = 0.01$  mm) represents the co-cured case typical of composite fabrication. For this case, yielding extended throughout the adhesive layer thickness to produce a long yield zone ahead of the delamination tip. The next case ( $t = 0.10$  mm) represents a typical adhesive bondline thickness and shows a larger yield zone extending through the adhesive thickness. Similarly, yielding also extended through the adhesive thickness for  $t = 0.20$  mm. For even larger values of  $t$ , however, the yield zones were smaller. The yield zone size increased and then decreased for increasing values of  $t$ , as shown in the third figure.

**Significance:** Interlaminar fracture toughness is widely believed to be proportional to the size of the yield zone at the delamination front. The present results can be interpreted to support this belief because the trend for the yield-zone-area curve agrees qualitatively with the well known observation that interlaminar toughness has a peak value when measured over a range of adhesive thickness. However, recent research in the Fatigue and Fracture Branch suggests that the plastic zone height rather than zone size should correlate with delamination toughness. The dashed curve for plastic zone height has an appropriate peak, which qualitatively supports the new interpretation of how adhesive layer thickness influences fracture toughness.

**Future Plans:** An elastoplastic numerical simulation of delamination growth will be developed to quantitatively correlate plastic zone height with energy dissipation (toughness) during delamination.

Figure 18(a).

## DOUBLE CANTILEVER BEAM SPECIMEN



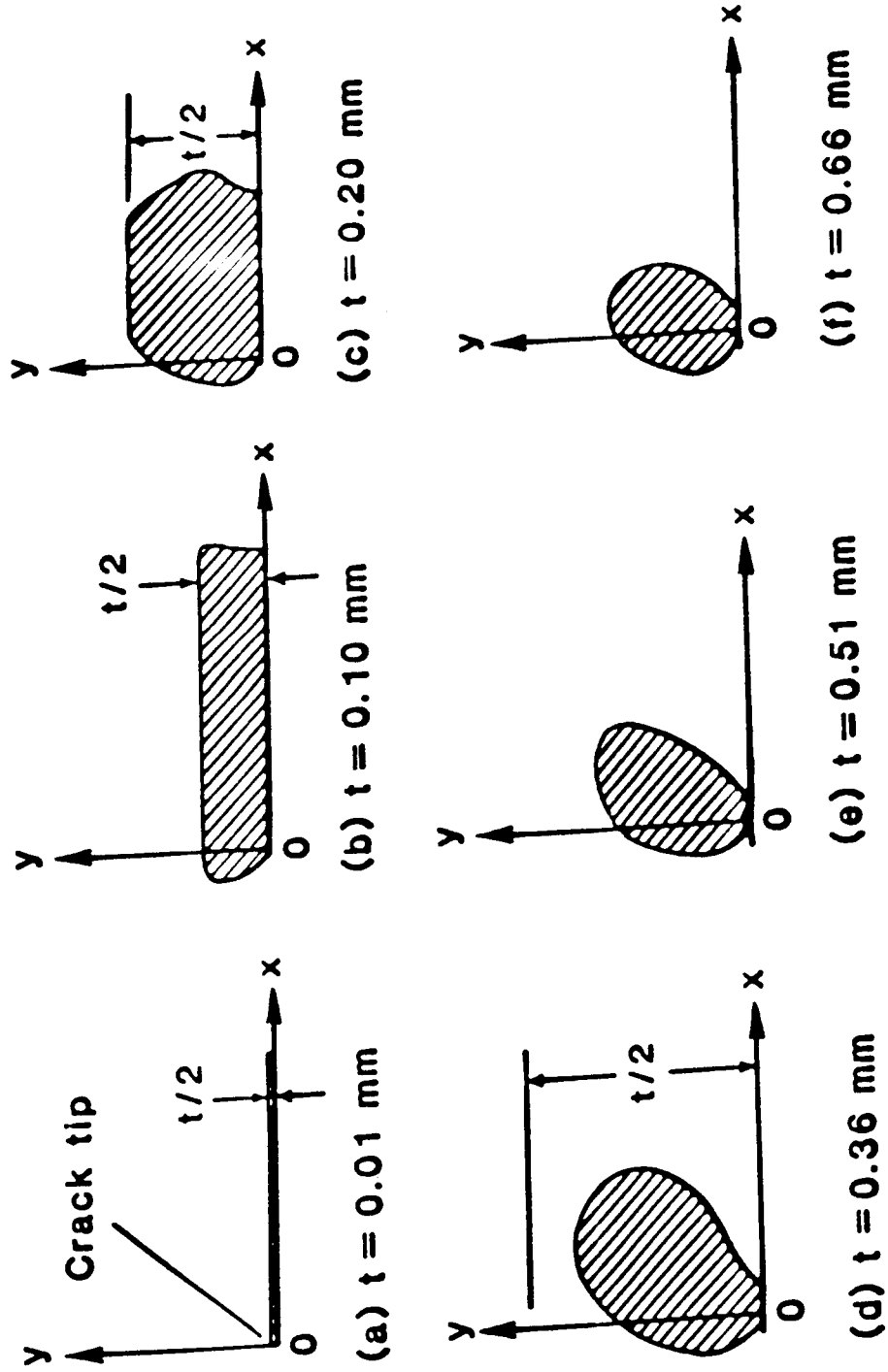


Figure 18(c).

# YIELD ZONE AREA AND HEIGHT

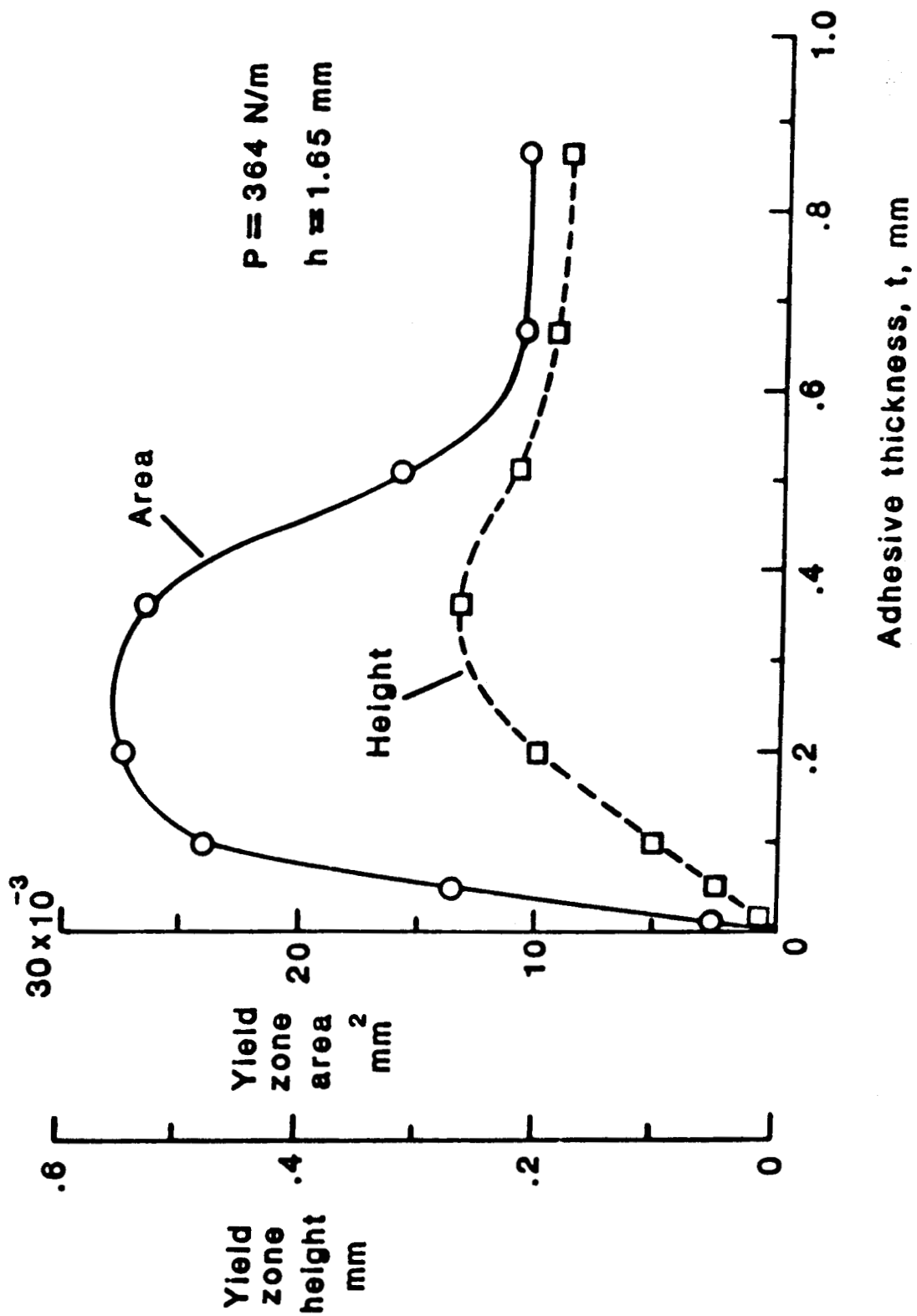


Figure 18(d).



## INTERLAMINAR SHEAR FATIGUE THRESHOLDS FOR COMPOSITE MATERIALS

T. Kevin O'Brien, G. B. Murri and S. A. Salpekar  
Fatigue and Fracture Branch  
Ext. 2093 September 1987  
RTOP 505-63-01

**Research Objective:** To evaluate the interlaminar shear fatigue thresholds for delamination of several composite laminates using the end-notched flexure test.

**Approach:** The end-notched flexure (ENF) test was used to determine interlaminar shear for delamination for T300/BP907 graphite-epoxy, S2/SP250 glass-epoxy, and AS4/PEEK graphite-thermoplastic. The ENF test consists of a small, 24-ply, unidirectional specimen with an insert at the mid-plane at one end. The specimen is loaded in 3-point bending, with the loads applied across the width, by means of pins which are free to roll. Specimens were cyclically loaded at 5 Hz until the onset of stable delamination growth was detected. The fatigue behavior was quantified in terms of the maximum cyclic mode II strain energy release rate,  $G_{IImax}$ . Delamination-onset threshold values were defined as the  $G_{IImax}$  values below which no delamination occurred after one million load cycles. Static interlaminar-shear fracture toughness,  $G_{IIC}$ , was also determined for each material.

**Accomplishment:** The results of the tests are shown in the figure. For all three materials, fatigue-induced delamination occurred at strain energy release rates significantly below the static fracture toughness values. Of the materials tested, the glass-epoxy material performed best in fatigue, but even for this material, the delamination threshold was only about 20 percent of the static fracture toughness. Residual static toughness tests on glass-epoxy specimens that had undergone one million cycles without delamination showed that the toughness had been significantly reduced by the cyclic loading.

**Significance:** These test results indicate that interlaminar-shear fatigue thresholds may be an important material property in the design of composite structures that will be subjected to load spectra containing many relatively low-level load cycles. Designs may be driven by the material fatigue performance rather than static toughness.

**Future Plans:** Because of the variability of properties of individual panels of PEEK, a detailed study will be conducted using a variety of tests, including static and cyclic ENF, to characterize the toughness of AS4/PEEK.

Figure 19(a).

# DELAMINATION-ONSET FATIGUE BEHAVIOR FOR INTERLAMINAR SHEAR

$R=0.1 \quad f=5 \text{ Hz}$

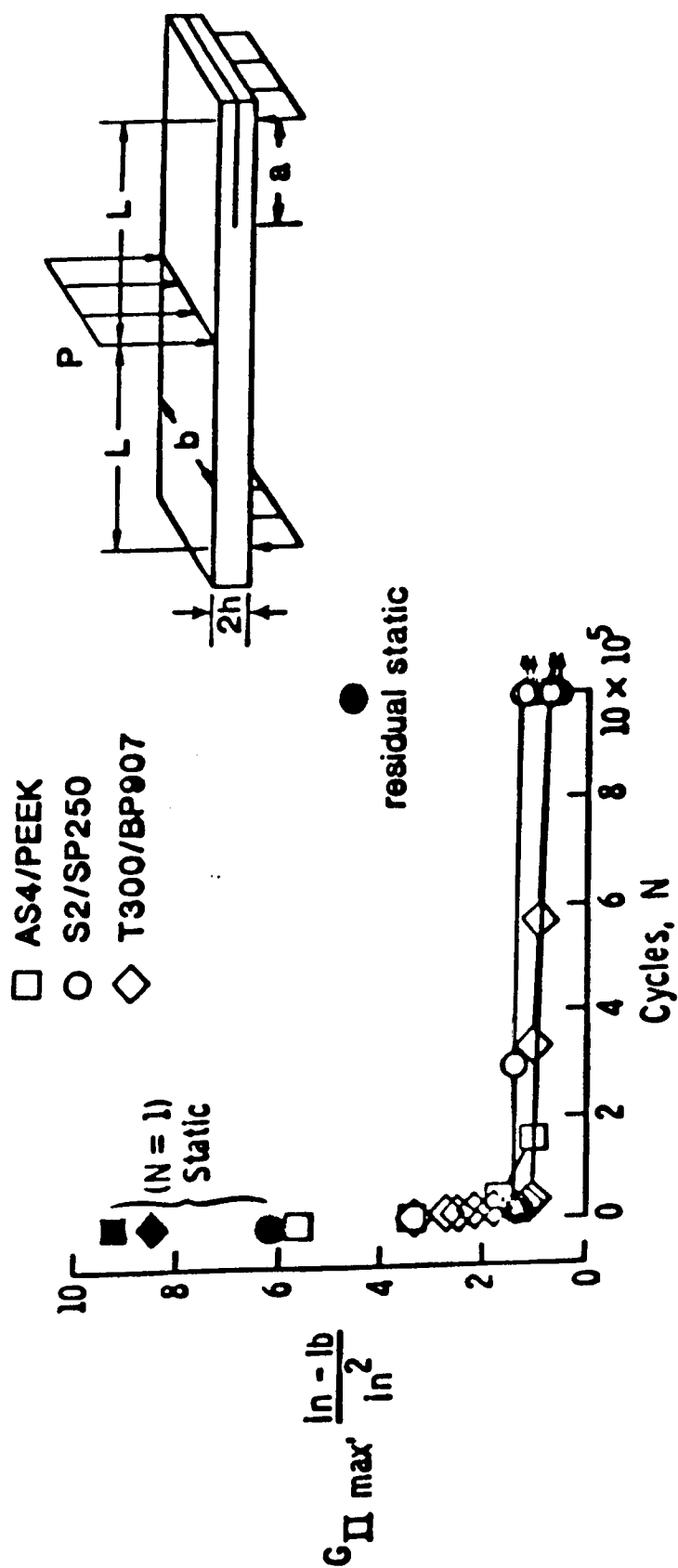


Figure 19(b).

## CALCULATION OF STRAIN-ENERGY RELEASE RATE DISTRIBUTION USING PLATE ANALYSIS

John D. Whitcomb and K. N. Shivakumar  
Fatigue and Fracture Branch  
Ext. 3046 November 1986  
RTOP 505-63-01

**Research Objective:** To develop a relatively inexpensive technique for calculating strain-energy release rate for use in predicting delamination in three-dimensional bodies.

**Approach:** Previously, the calculation of the distribution of strain-energy release rate for three-dimensional (3-D) bodies required 3-D solids analysis, which is very expensive. To obtain the strain-energy release rate more economically, a plate analysis technique was developed that is inherently much less expensive than 3-D solids analysis.

**Accomplishment:** A popular technique for calculating strain-energy release rate is the virtual crack closure technique. This technique relates strain-energy release rate to the energy required to close a crack over a very small distance. Traditional implementation of this technique requires parameters which are available from 3-D solids analysis but not from plate analysis. In the current effort, a virtual crack closure technique was developed which only includes terms available from plate analysis. As a check of the new method, analyses of a transversely-loaded, delaminated region were performed using plate analysis and 3-D analysis. The figure shows a sketch of the configuration and the distribution of strain-energy release rate obtained using the two analyses. The agreement is quite good.

**Significance:** It is economically impractical to use 3-D solids analysis for analyzing numerous configurations. In many cases, plate analysis offers a much less expensive alternative. Using the formula developed in this effort will permit relatively inexpensive calculation of strain-energy release rates for use in delamination prediction.

**Future Plans:** The possibility of estimating the mode I and mode II components of the total strain-energy release rate will be investigated.

Figure 20(a).

# Distribution of Strain-Energy Release Rate

( For  $X = a/2$  )

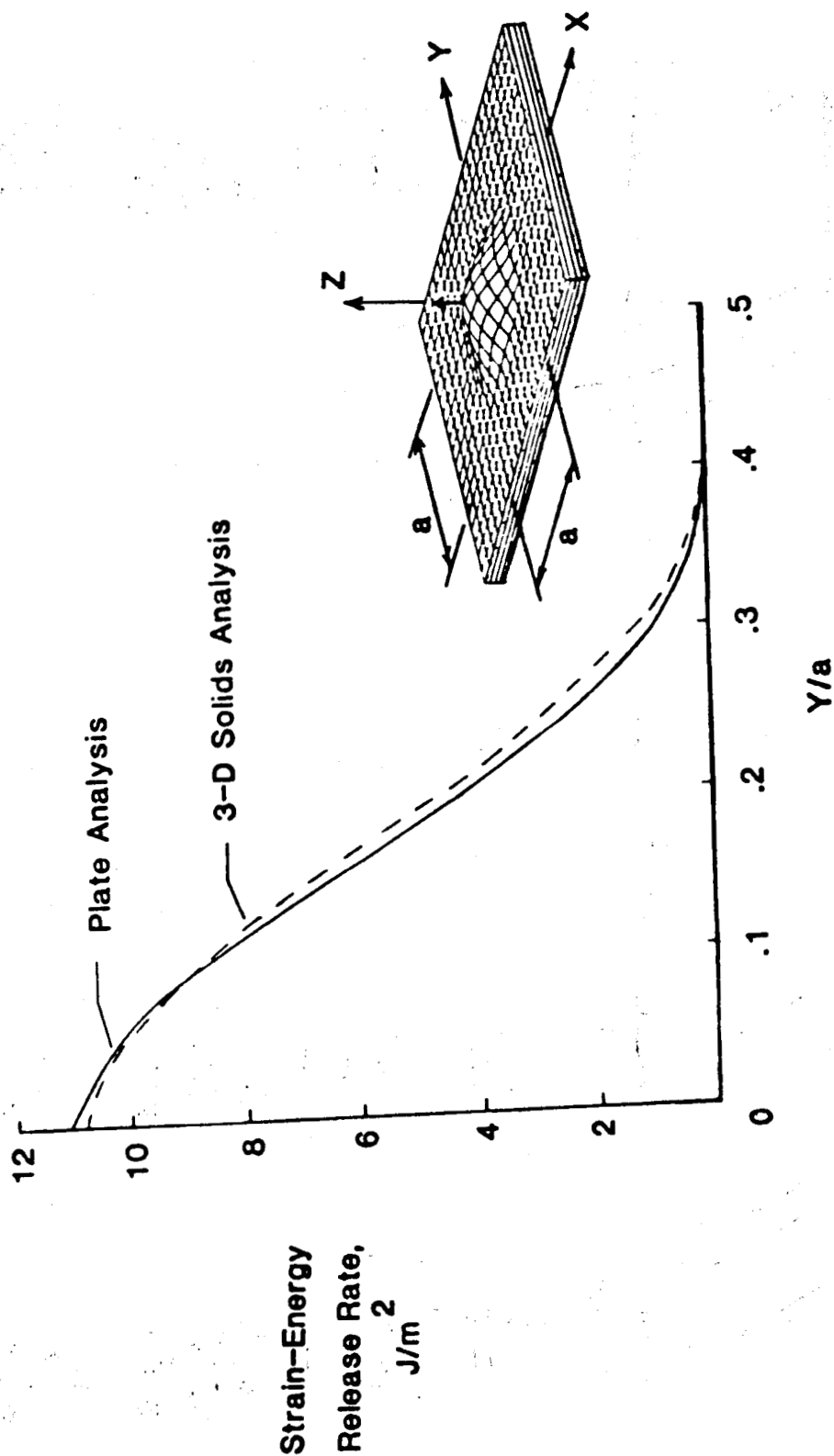


Figure 20(b).

## BOUNDARY FORCE METHODS FOR ANALYZING CRACKED LAMINATES

P. W. Tan and C. A. Bigelow  
Fatigue and Fracture Branch  
Ext. 3047      January 1987  
RTOP 505-63-01

**Research Objective:** To extend the Boundary Force Method (BFM), a form of an indirect boundary element method, to the analysis of orthotropic laminates.

**Approach:** To extend the BFM to composite materials, the orthotropic elasticity solution for a concentrated horizontal and vertical force applied at a point in a cracked infinite sheet was used as the fundamental solution. The necessary stress functions for this fundamental solution were formulated using the complex variable theory of elasticity. The simple configuration of a center-crack specimen subjected to uniaxial tension was used to evaluate the BFM for composite materials.

**Accomplishment:** The figure shows the normalized stress-intensity factors for a center-crack tension specimen with  $H/W = 3$  for three graphite/epoxy laminates:  $[0/\pm 45/90]_s$ ,  $[\pm 45]_2s$ , and  $[0]$ . The curves represent the current BFM results and the symbols represent results from a boundary integral solution by Snyder and Cruse. As shown in the figure, the BFM results agree well (within  $\pm 3$  percent) with results from Snyder and Cruse. This close agreement validates the extension of the BFM to composite laminates.

**Significance:** The orthotropic BFM can now be applied to complex composite configurations for which no solutions exist. In the BFM, the fundamental solution models the crack faces, exactly satisfying the stress-free conditions there; thus, the numerical analysis does not have to model the crack faces. Only the boundaries of the region of interest are modeled, resulting in a significant savings in the number of degrees of freedom required for an accurate analysis and, consequently, in the time needed for modeling.

**Future Plans:** A concentrated moment will be used with the horizontal and vertical forces in the formulation of the fundamental solution to speed convergence. More complex configurations for which orthotropic solutions are currently not available will be analyzed using the BFM.

**Reference:** Snyder, M. D.; and Cruse, T. A.: Crack tip stress intensity factors in finite anisotropic plates. Air Force Materials Laboratory, AFML-TR-73-209, August 1973.

Figure 21(a).

# BOUNDARY FORCE METHOD FOR ANALYZING CRACKED LAMINATES

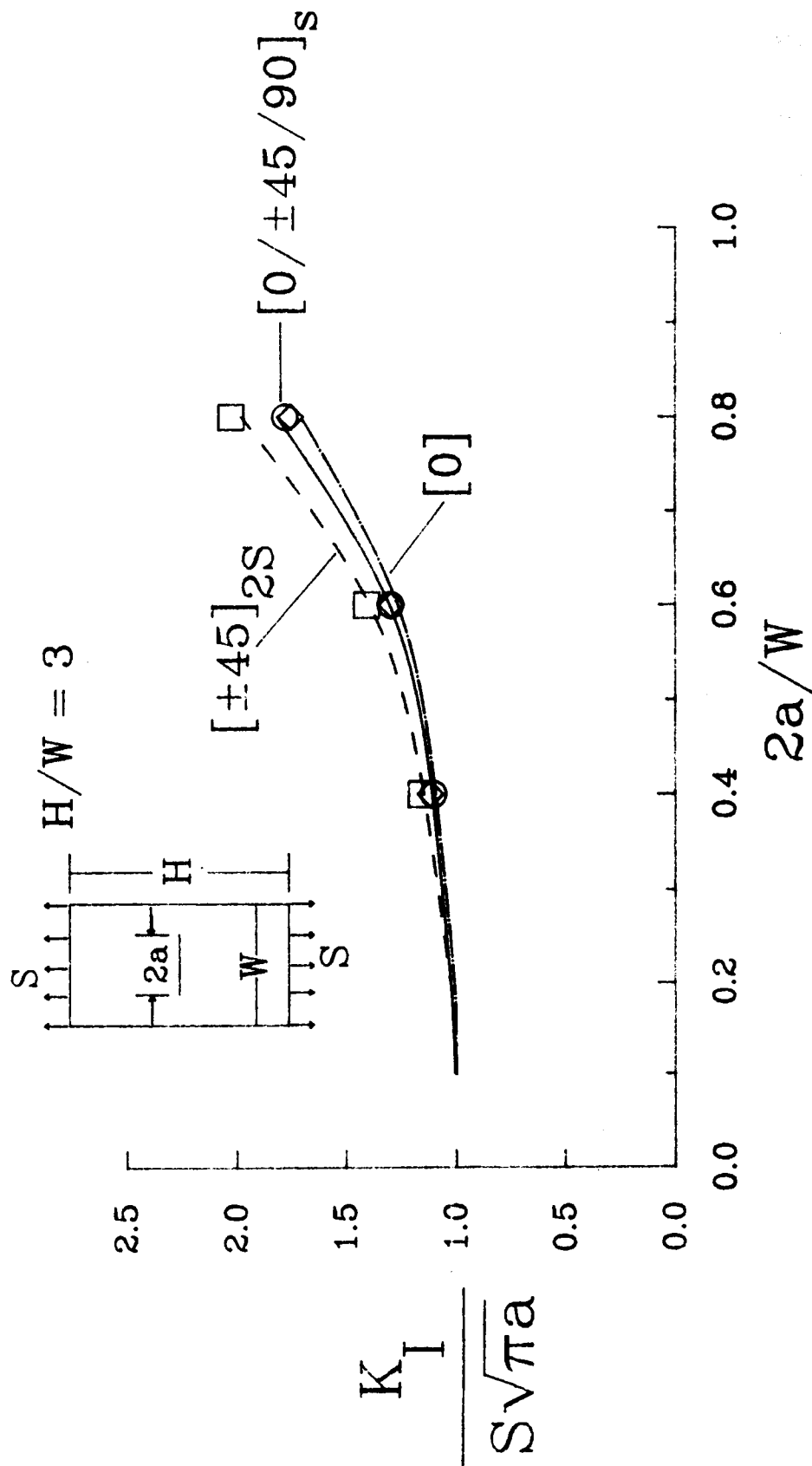


Figure 21(b).

## STRAIN ENERGY RELEASE RATES FOR EDGE-DELAMINATED COMPOSITE LAMINATES

I. S. Raju, J. H. Crews, Jr. and M. A. Aminpour  
Fatigue and Fracture Branch  
Ext. 3178 March 1987  
RTOP 505-63-01

**Research Objective:** To evaluate the accuracy of finite-element models used to obtain mode-I, mode-II, mode-III and total strain energy release rates for edge-delaminated composite laminates.

**Approach:** Composite laminates have thin resin layers of thickness 0.0004 in. (about 1/20 of the ply thickness) between individual plies. Finite-element modeling of such a practical laminate requires considerably larger number of degrees of freedom than models in which the resin layers are neglected ("bare" interface models). Therefore, in this research the strain energy release rates obtained with both the resin layer models and the "bare" interface models are compared. Both the models used a quasi-three-dimensional finite-element analysis and a virtual crack closure technique to compute the strain energy release rates.

**Accomplishment:** The figure shows the mode-I, mode-II, mode-III and the total strain energy release rates for an edge-delaminated [0/±35/90]<sub>s</sub> laminate with a delamination at the -35/90 interface. The strain energy release rates are plotted against the size of the delamination tip elements ( $\Delta/h$ ). The abscissa is plotted on a log scale. The "bare" interface model (circular symbols) do not show any convergence for the individual modes as smaller delamination tip elements are used, while the total strain energy release rates do remain unchanged with mesh refinement. In contrast, the resin layer model (horizontal dashed lines) shows convergence for the individual as well as the total strain energy release rates with mesh refinement. The reason for the non-convergence of the "bare" interface model was explored and it was determined that the non-convergent behavior was inherent in the elasticity formulation of problems involving crack tips between dissimilar materials. Therefore, the non-convergence of the finite-element solution was to be expected. Although the "bare" interface model does not produce accurate results for small elements, the results for larger elements ( $\Delta/h = .25$  to  $.50$ ) were within four percent of results from the resin model.

**Significance:** The current research explained the difference in convergence behavior of the "bare" and resin interface models. The research also showed that the "bare" interface models, which are easier to model and require significantly fewer degrees of freedom than resin layer models, can be useful if used judiciously.

Figure 22(a).

# STRAIN ENERGY RELEASE RATES FOR EDGE DELAMINATIONS

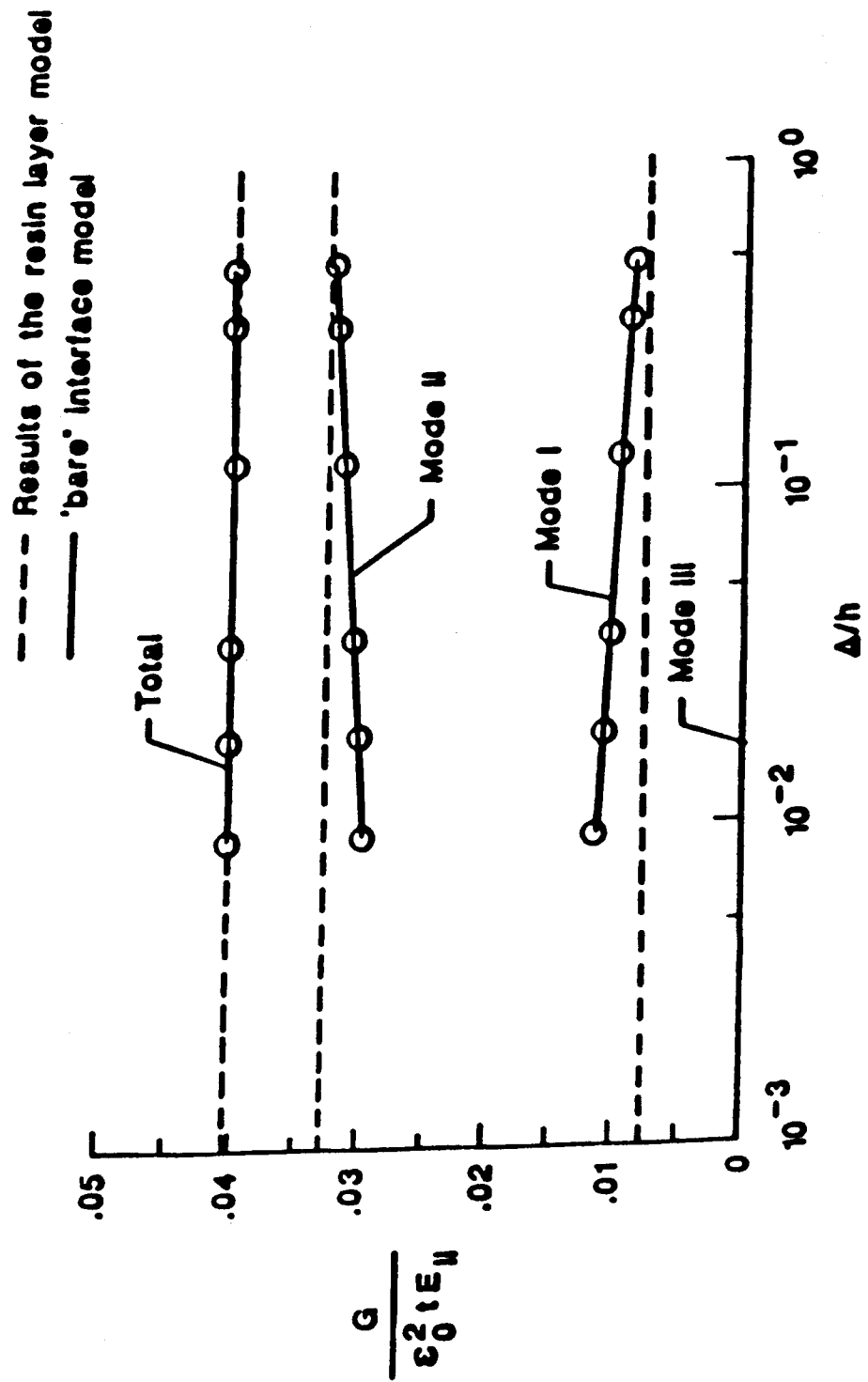


Figure 22(b).



## FIBER-RESIN MICROMECHANICS ANALYSIS OF DELAMINATION

John H. Crews, Jr., K. N. Shivakumar and I. S. Raju

Fatigue and Fracture Branch  
Ext. 3048 May 1987  
RTOP 505-63-01

**Research Objective:** To develop a micromechanics analysis of resin yielding near the delamination front in a double cantilever beam (DCB) specimen.

**Approach:** A local-global approach was used with a finite-element procedure to analyse a DCB specimen. First, a 3-D finite-element model was developed for an orthotropic, homogeneous DCB specimen and was used to calculate displacements near the delamination. The displacements were found to be uniform along most of the delamination front, varying only near the specimen edge. The displacements computed for the interior of the specimen were then imposed on a local fiber-resin model of a small 3-D region near the delamination. The DCB sketch in the figure shows this local 3-D region, which includes the four fibers closest to the delamination. For convenience, the fibers were assumed to be arranged in a square array; therefore, local symmetry existed about a plane through the center of the fibers. This local fiber-resin model had about 23,000 nodes and 69,000 degrees-of-freedom, and was analyzed using the LaRC CDC-205 (VPS-32) super computer.

**Accomplishment:** Elastic stresses were computed for a T300/5208 graphite epoxy DCB specimen, loaded up to the critical condition for delamination growth ( $G_{Ic} = 85 \text{ J/m}^2$ ). The local stresses corresponding to delamination growth were then used with the von Mises yield criterion to estimate the extent of resin yielding near the delamination front. The shaded regions in the figure indicate yielding in a section ( $x = 0$  plane) through the model and along its front face. Yielding developed in the resin-rich layer ahead of the delamination, as expected; however, it also developed in three regions between the fibers, because of stress concentrations in those regions. These results suggest that delamination is accompanied by energy-dissipating yielding within the laminate, even for this brittle T300/5208 material system.

**Significance:** The yielding in this fiber-resin model was compared to that for a crack in an all-resin specimen loaded to the same critical growth condition. The yield zone area for the fiber-resin case was larger than in the all-resin case. The fibers appear to promote yielding and therefore should cause the laminate fracture toughness to be greater than the all-resin case. This trend has been observed for low-toughness resins but has previously been attributed to "fiber-bridging" effects. This study has identified yielding between adjacent fibers as an energy-dissipation mechanism during delamination.

**Future Plans:** The present elastic micromechanics study will be extended to include elastoplastic analyses of tough-resin laminates.

Figure 23(a).

# FIBER-RESIN MICROMECHANICS ANALYSIS OF DELAMINATION

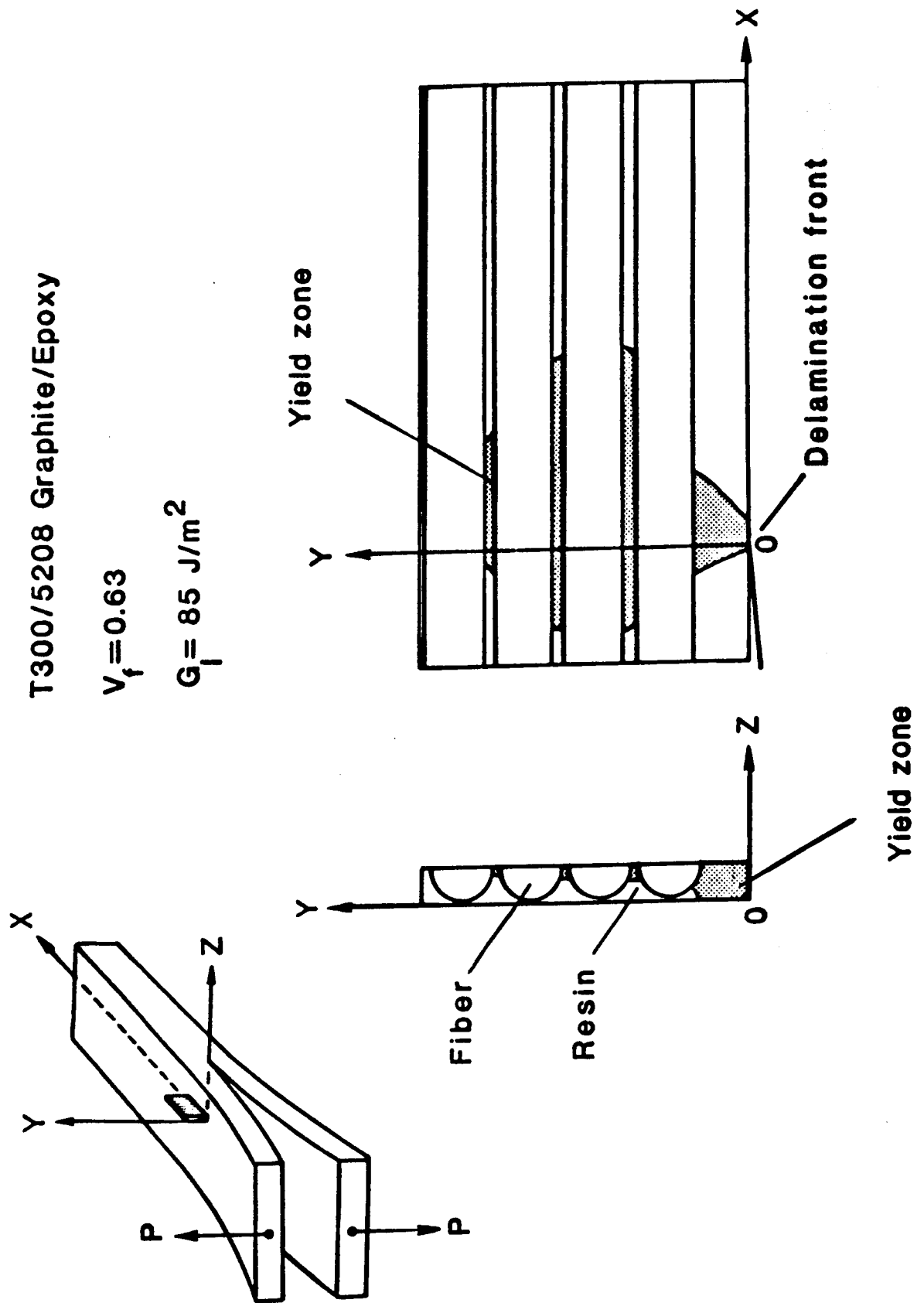


Figure 23(b).

S. A. Salpekar, I. S. Raju and T. K. O'Brien  
 Fatigue and Fracture Branch  
 Ext. 2093 May 1987  
 RTOP 505-63-01

**Research Objective:** To evaluate the mode-II strain energy release rate,  $G_{II}$ , for the end notched flexure (ENF) specimen using beam theory and determine its validity by comparison with a finite-element analysis.

**Approach:** The ENF test is used to determine the mode-II critical strain energy release rate for delamination in composite materials, and is one of four test methods being considered as ASTM standard tests for measuring interlaminar fracture toughness. Therefore it is necessary to establish a theoretical, as well as experimental, basis for calculation of  $G_{II}$  from this test. The ENF test is a three point bend test of a 24 ply unidirectional composite with a delamination insert at the mid-surface on one end. The crack length,  $a$ , and beam span,  $l$ , as well as material properties, may influence the ENF test. Therefore, theoretical estimation of  $G_{II}$  for this test must be accurate for any material and  $a/l$  ratio chosen. To demonstrate this accuracy, a finite element analysis was performed. Finite-element analysis solves the boundary problem accurately and yields  $G_{II}$  and compliance values. Classical beam theory with shearing deformation gives the corresponding approximate values. The two methods were compared for the ENF test for a wide range of  $a/l$  ratios and material properties.

88

**Accomplishment:** A finite-element analysis of the ENF specimen was performed for various delamination lengths. A wide range of material properties, including glass/epoxy and graphite/PEEK, were analyzed. The virtual crack closure technique (VCCT) was used to calculate  $G_{II}$  using local forces and displacements around the delamination tip. Alternatively, the compliance values from the analysis are used to calculate  $G_{II}$  as a global change in energy with delamination length. The values of  $G_{II}$  thus obtained on local and global basis agreed within one percent. The equation for compliance, which includes bending and shear deformation effects, is available in the literature. The derivative of this equation yields an expression for approximate calculation of  $G_{II}^{SH}$ . As shown in the figure, the corresponding  $G_{II}^{SH}$  values were in close agreement with the finite-element solution; the differences were less than eight percent.

**Significance:** This study indicates that beam theory with shear deformation gives a fairly accurate value of  $G_{II}$  in the ENF test, and establishes the validity of using the rate of change in compliance with crack length to measure  $G_{II}$  in the ENF test.

Figure 24(a).

# COMPARISON OF $G_{II}$ FROM FINITE ELEMENT ANALYSIS AND BEAM THEORY WITH SHEAR DEFORMATION

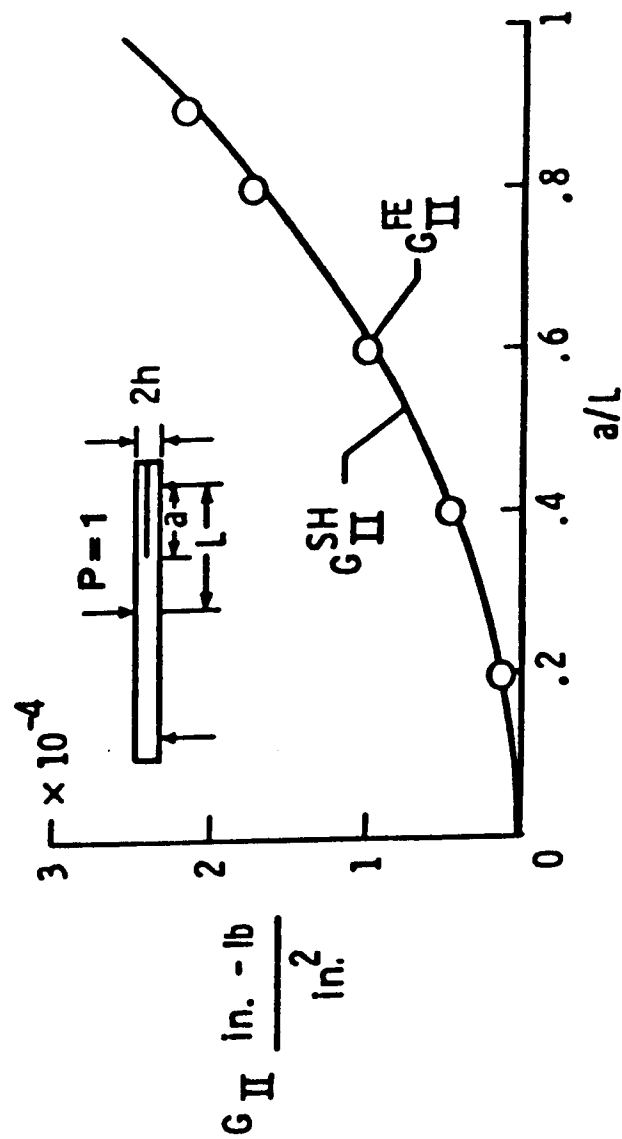


Figure 24(b).

This page intentionally left blank.

## FINITE-ELEMENT-ALTERNATING METHOD FOR CRACK ANALYSES

I. S. Raju, S. N. Atluri, and J. C. Newman, Jr.  
Fatigue and Fracture Branch  
Ext. 3178 July 1987  
RTOP 505-63-01

**Research Objective:** To study the performance of the finite-element-alternating method in the analysis of cracked solids by comparing it to the conventional finite-element method.

**Approach:** A three-dimensional finite-element-alternating method code was written for stress-intensity factor analyses of elliptical or part-elliptical cracks in solids. This code uses the solution of an embedded elliptical crack in an infinite solid subjected to arbitrary crack-face tractions. The method is based on Schwartz-Neumann alternating method. The finite-element method is used in conjunction with the continuum solution method to alternate between the two methods to satisfy the required boundary conditions.

**Accomplishment:** The first figure shows the stress-intensity factor distributions obtained by the finite-element-alternating and conventional methods for a quarter-elliptical corner crack subjected to remote tension. The quarter-elliptical crack is very oblong and shallow. The uncracked body was modeled with a simple rectangular mesh with about 3000 degrees of freedom. The stress-intensity results agreed well with the conventional finite-element method using about 6500 degrees of freedom. The computing time for the alternating method was about 450 seconds and for the conventional method was about 400 seconds on the VPS-32 computer. For the alternating method, most of the computing time was used in factorizing the global stiffness matrix. But after this is accomplished, little additional computing time is required to analyze other crack shapes and sizes.

**Significance:** The second figure shows the stress-intensity factors for three crack shapes and three crack sizes (9 crack configurations) obtained by this method. The computing time required for these cases is 630 seconds. The conventional finite-element method requires nine separate calculations and therefore requires  $9 \times 400 = 3600$  seconds. Thus, the computing time with the alternating method was about one-sixth that for the conventional finite-element method. The alternating method is a very efficient tool for analyzing a range of crack configurations. Further, simple rectangular idealizations are much easier to model than the complex modeling needed with the conventional finite-element method.

**Future Plans:** The finite-element-alternating method will be applied to configurations for which very few stress-intensity solutions are available. Further, the performance of the method will be studied in mixed-mode loading situations.

# STRESS-INTENSITY FACTORS FOR A CORNER CRACK

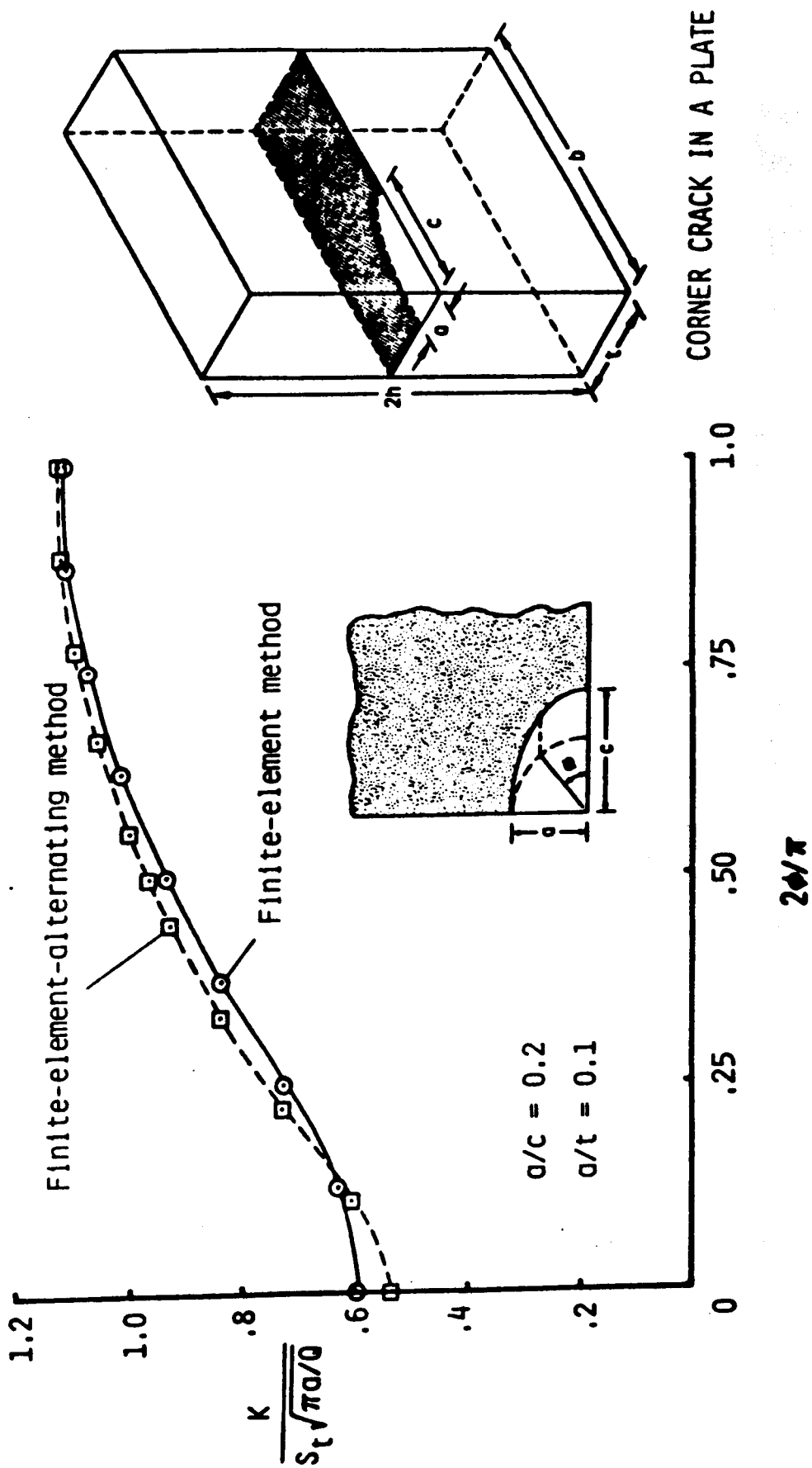


Figure 25(b).

# STRESS-INTENSITY FACTORS FOR VARIOUS CRACK SHAPES AND SIZES

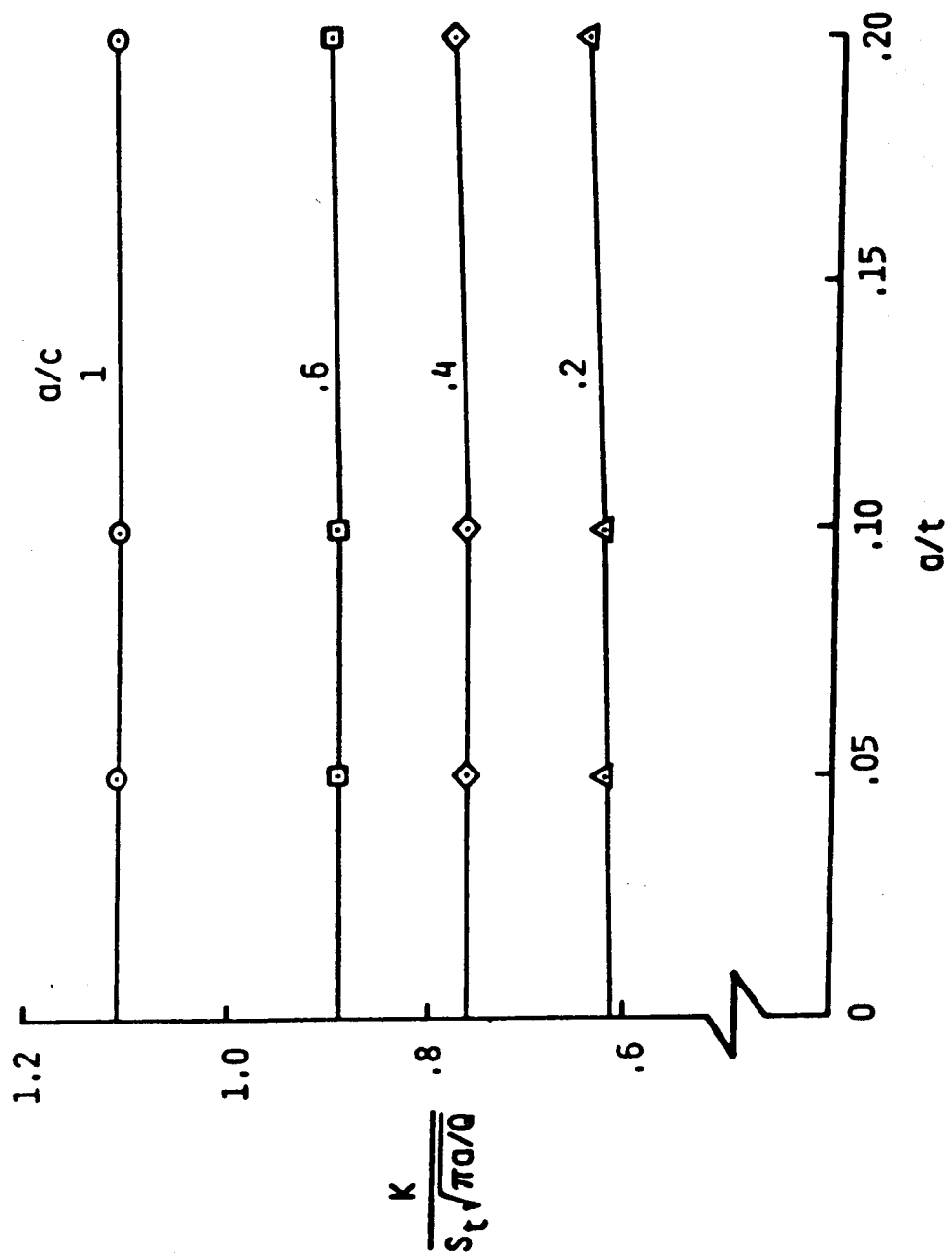


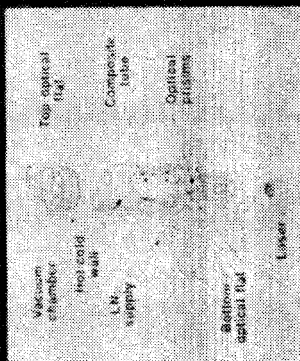
Figure 25(c).



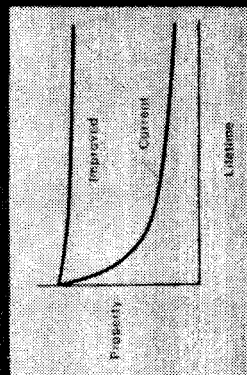
# APPLIED MATERIALS

## MATERIALS FOR SPACE STRUCTURES

### DIMENSIONAL STABILITY

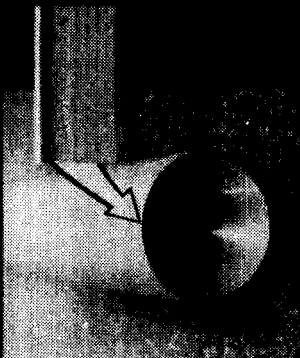


### Laser Interferometry

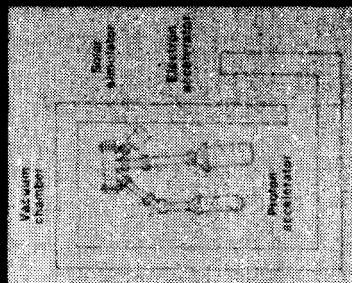


### Durable Materials

### PROTECTIVE COATINGS

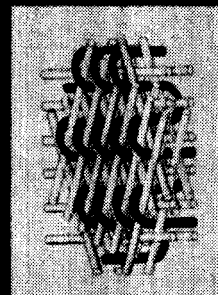


### Coated Composite Tube

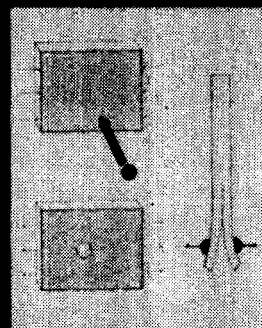


### Radiation Effects

## AIRCRAFT COMPOSITE MATERIALS

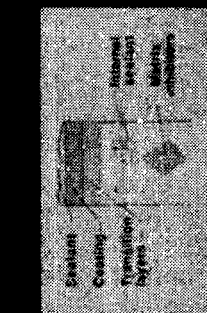


### Material Forms and Processing



### Material Testing and Analysis

## CARBON-CARBON COMPOSITES



### Oxidation Resistant Hot Aerostructure



Figure 26.

APPLIED MATERIALS BRANCH  
FIVE YEAR PLAN

MAJOR THRUST	FY87	FY88	FY89	FY90	FY91	EXPECTED RESULTS
Space materials						Materials concepts for space station structure
						New concepts for space-stable materials
						Low CTE composites for precision structures
						Life assessment of SDA C-C for NASP control surfaces
High temperature materials (>1800°F)						Strong delamination resistant, lightweight C-C for aerostructure
						Extended-life C-C for TPS and hot structure
						Efficient composite materials for structural applications
						Demonstrated tough, efficient, and cost effective materials
Composite materials for rotorcraft and aircraft structures						Demonstrated long-term durability for tough composites

Figure 27.

## DEVELOPMENT OF PROTECTIVE COATINGS FOR COMPOSITE TUBES

Louis A. Teichman  
Applied Materials Branch  
Ext. 3027      October 1986  
RTOP 506-43-21

**Research Objective:** To develop protective coatings for graphite/epoxy tubes proposed for Space Station truss structure.

**Approach:** This research was performed by the Boeing Aerospace Corporation under NASA contract. Boeing/NASA defined the structural configuration of the composite tubes which maximizes stiffness and results in little microcracking. Coatings were developed which are suitable for use in the low Earth orbit (LEO) environment. Coated composite tubes were subjected to a simulated LEO environment and tested for degradation of mechanical and thermo-optical properties.

**Accomplishment:** Composite tubes constructed of a high-modulus fiber (Union Carbide P75S) and a 350°F-cure epoxy resin (Fiberite 934) and layed up with alternating shallow (20°) angles and 0° plies result in a stiff (35 Msi) structural element suitable to be used in a Space Station truss. When these tubes were wrapped with a chromic acid anodized aluminum foil or a sputter-coated (Al/SiO<sub>2</sub>) aluminum foil, they yielded a broad range of thermo-optical properties (solar absorptance,  $\alpha_s = 0.20$  to 0.35; thermal emittance,  $\epsilon = 0.15$  to 0.25). The coated aluminum wrapping served to moderate thermal excursions in LEO without significant change in modulus of thermal expansion properties. The program also demonstrated that measurements of simple optical properties, from which  $\alpha_s$  and  $\epsilon$  are derived, are similar for flat and curved surfaces and might therefore eliminate the need for extensive optical testing of tubes. Furthermore, when the coated tubes were subjected to such LEO parameters as thermal cycling, solar radiation, atomic oxygen, and vacuum for periods equivalent to several months in space, they suffered no microcracks or serious loss of structural or thermo-optical properties.

**Significance:** The project demonstrated that high quality composite tubes can be readily fabricated from graphite/epoxy prepreg adhesively wrapped with a coated aluminum foil. These tubes showed promise of meeting the structural requirements for a Space Station truss structure with regard to stiffness, crack resistance, and durability in the expected space environment.

**Future Plans:** In the coming year, coated composite tubes will be subjected to 10,000 thermal cycles between +150°F and -150°F. In addition, tubes will be fabricated in lengths up to 10 ft with a straightness of  $\pm 15$  mil. Also, coated composite tubes will be subjected to other LEO parameters for greater periods of time.

Figure 28(a).

# LONGITUDINAL ELASTIC MODULUS AS A FUNCTION OF PLY ORIENTATION

Analysis of P75S/934 flat composite plate

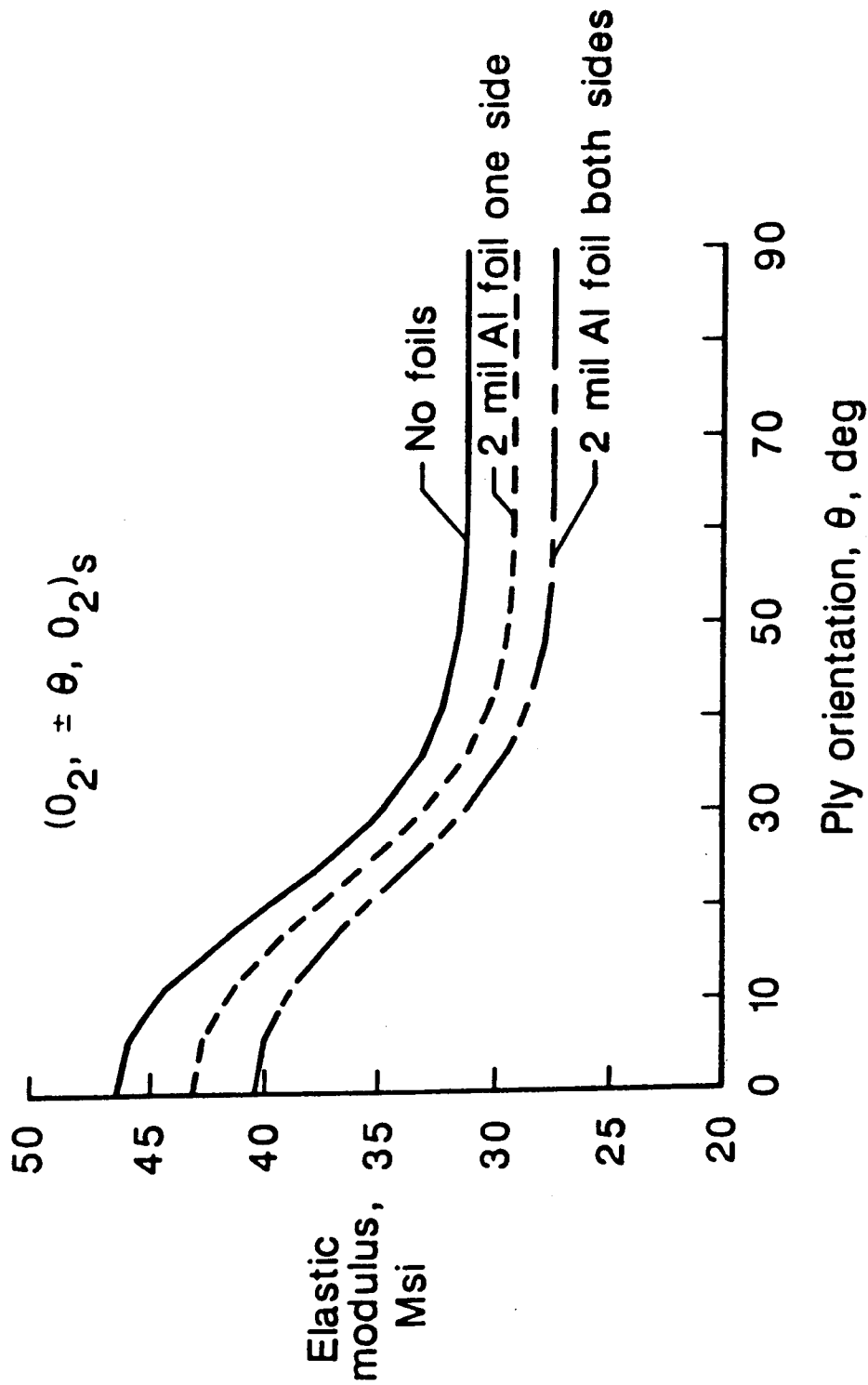


Figure 28(b).

# LONGITUDINAL COEFFICIENT OF THERMAL EXPANSION AS A FUNCTION OF PLY ORIENTATION

Analysis of P75S/934 flat composite plate

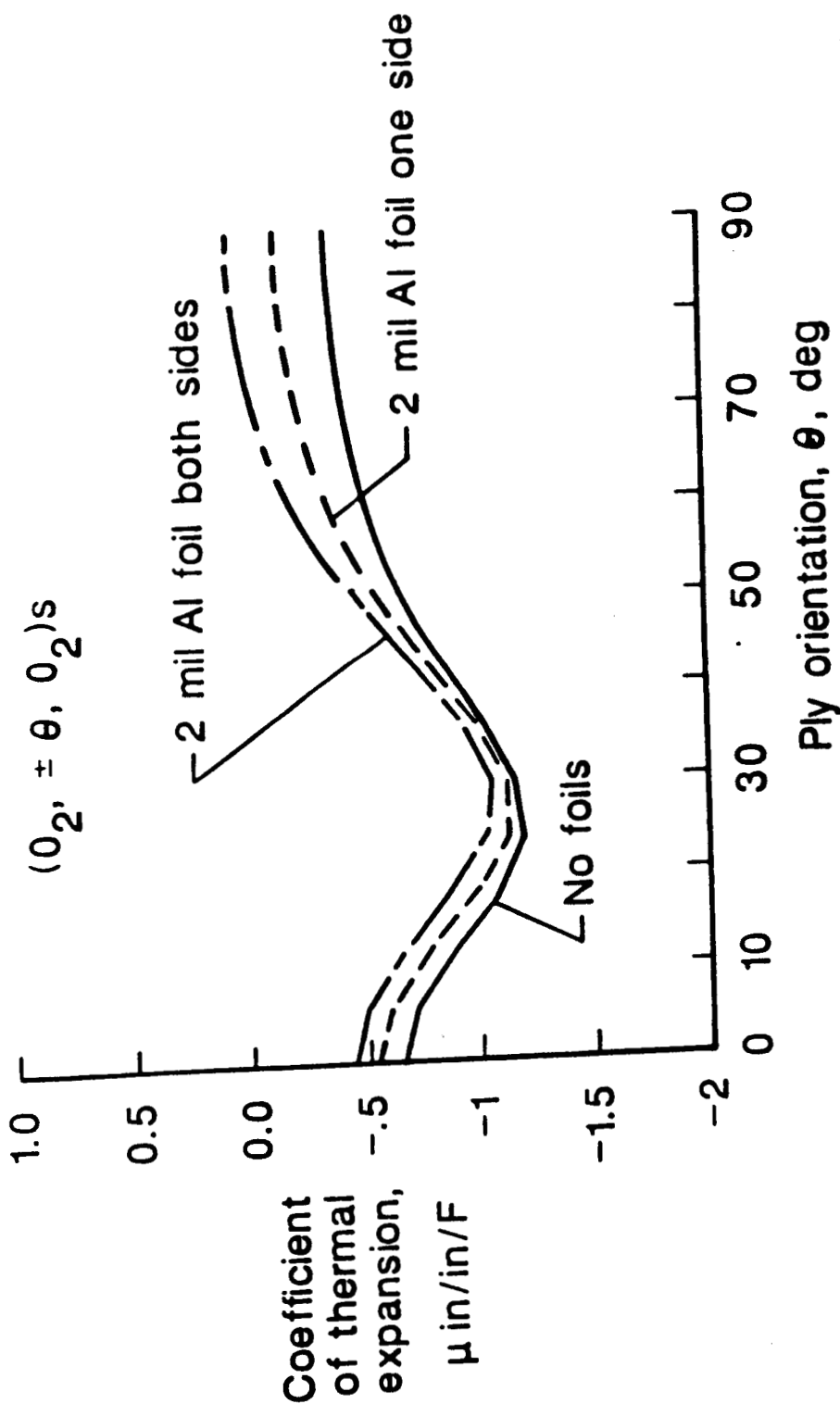


Figure 28(c).

# REFLECTANCE OF CHROMIC ACID ANODIZED ALUMINUM SPECIMENS

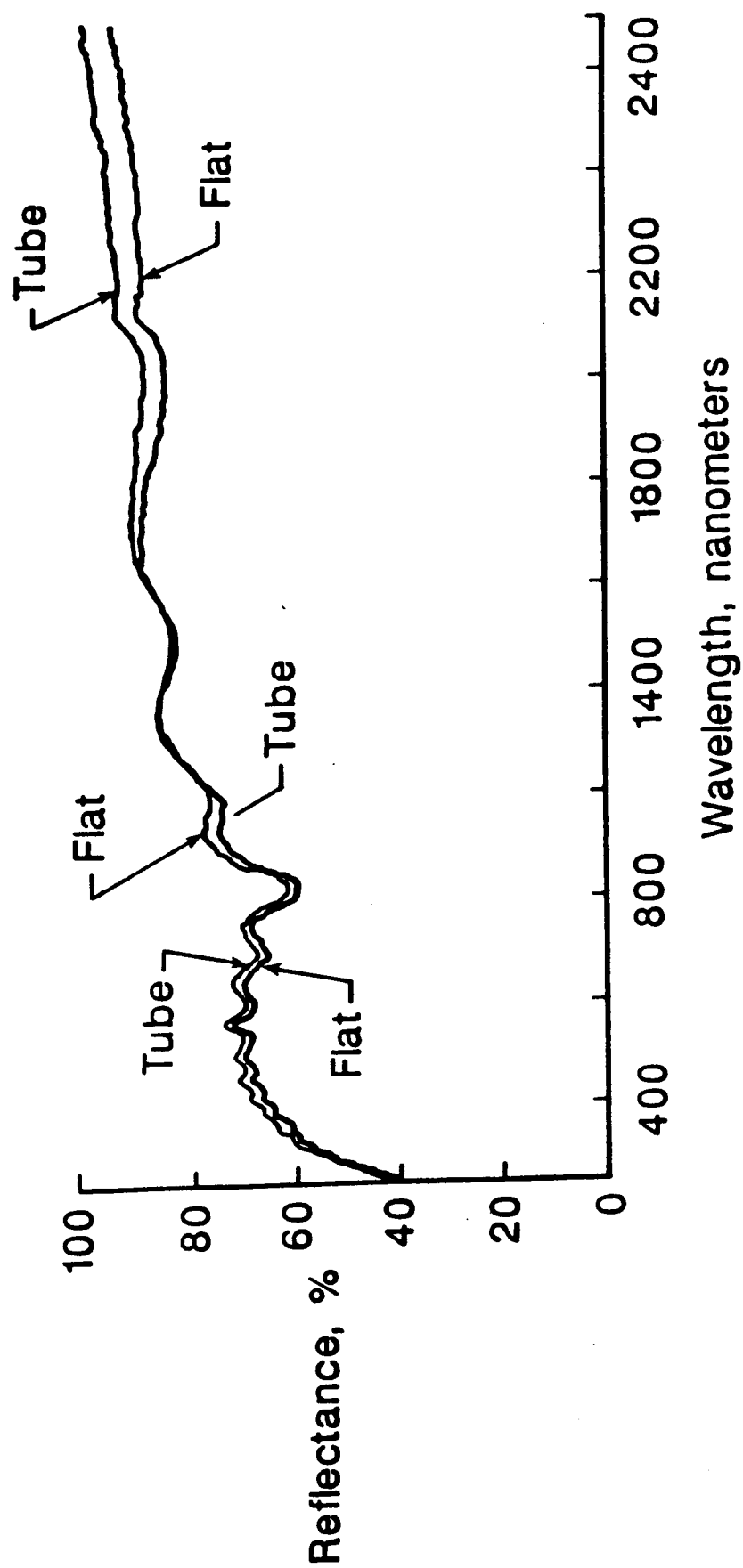


Figure 28(d).

# A COMPARISON OF THE EFFECTS OF SIMULATED LOW-EARTH AND GEOSYNCHRONOUS ORBIT EXPOSURE ON COMPOSITE MATERIALS

Joan G. Funk  
Applied Materials Branch  
Ext. 4582 June 1987  
RTOP 506-43-21

**Research Objective:** To evaluate the effects of simulated space environmental exposure on several polymer-matrix composites for spacecraft applications.

**Approach:** Characterize the materials' response to 500 thermal cycles simulating low-earth orbit (LEO) and to  $10^{10}$  rads exposure to 1 MeV electrons followed by 500 thermal cycles simulating geosynchronous orbit (GEO). Two different upper temperature limits, 65°C and 93°C, were used during thermal cycling to insure that the glass transition temperature ( $T_g$ ) of the material was not exceeded. The lower thermal cycling temperature was -150°C. The amount of microdamage in each composite system was measured by the microcrack density as determined by X-ray photography.

**Accomplishment:** The figure shows the X-ray photographs for T300/934. The baseline material, which had not undergone either thermal cycling or radiation exposure, shows no evidence of microcracking. The X-ray photograph of the material exposed to simulated LEO showed microdamage in the form of microcracks in the 0° and 90° directions. The T300/934 material exposed to simulated GEO had an even higher microcrack density with microcracks in all ply directions.

The table summarizes the observed microdamage for all six of the commercially available aerospace material systems studied and gives a brief description of the materials. For the baseline materials, only the C6000/P1700 system exhibited microcracks in the as-fabricated condition. The simulated LEO environment produced major microdamage in all the composites except the T300/BP907 system and the AS4/PEEK system. The GEO simulated environment produced microcracking in all systems. Overall, the microcrack density for all materials was greater than that found following the LEO simulation showing that radiation affects the matrix in all of the composites and thus the thermal cycling response. The results show that the composite system with the least sensitivity to microdamage during LEO simulated exposure was the most damaged by simulated GEO environment. Thus, composite materials suitable for LEO spacecraft applications may not have the required durability for long-term GEO missions.

**Significance:** This study evaluated the space durability of a variety of composites with matrices ranging from a brittle epoxy to a tough semicrystalline thermoplastic.

**Future Plans:** The composite materials which showed the best performance in this study will be evaluated to determine which properties lead to their improved space durability.

Figure 29(a).



# X-RAY PHOTOGRAPHS OF T300/934

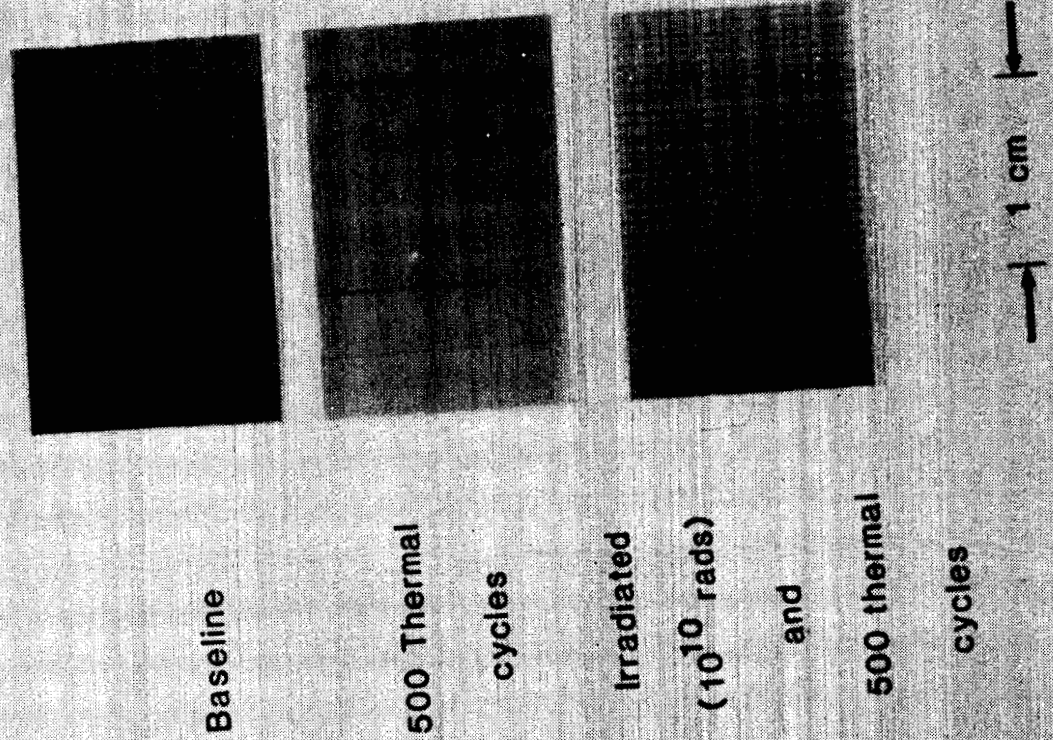


Figure 29(b).



# SUMMARY OF MICRODAMAGE IN COMPOSITE MATERIALS

## MICROCRACK DENSITY, CRACKS/CM

	MATRIX DESCRIPTION	BASELINE	THERMAL CYCLED	IRRADIATED AND THERMAL CYCLED 1
T300/934	177°C CURE, MY720 BASED EPOXY	0	7	17
T300/BP907	177°C CURE, SINGLE PHASE TOUGHENED EPOXY	0	0	>50 2
T300/CE339	121°C CURE, 2-PHASE ELASTOMER TOUGHENED EPOXY	0	8	25
C6000/PI1700	POLYSULFONE, AMORPHOUS THERMOPLASTIC	5	21	24
AS4/PPS	POLYPHENYLENE SULFIDE SEMICRYSTALLINE THERMOPLASTIC	0	19	22
AS4/PEEK	POLYETHERETHER KETONE, SEMICRYSTALLINE THERMOPLASTIC	0	1	5

- 1 IRRADIATED TO 10<sup>10</sup> RADS AT 5 x 10<sup>7</sup> RADS/HR FOLLOWED BY 500 THERMAL CYCLES.  
 2 CRACKING AND DELAMINATION EXTENSIVE.

Figure 29(c).

## THERMALLY INDUCED TWIST IN COMPOSITE TUBES

Stephen S. Tompkins and Carl Q. Rousseau  
Applied Materials Branch  
Ext. 4558 August 1987  
RTOP 481-33-13

**Research Objective:** To measure and model the dilatation and stress state of tubular structural elements subjected to thermal cycles typical of Earth orbiting spacecraft.

**Approach:** Measure the thermal expansion and distortion of high modulus graphite fiber reinforced epoxy composite tubes subjected to thermal cycles typical of the Space Station. Develop analytical models of the thermal expansion, distortion, and stress state using elasticity theory with temperature-dependent material properties. Compare the analytical and experimental results and modify the analysis as required.

**Accomplishment:** Thermal distortions of tubes made of different composite materials, P75S/ERLX1962A, T300/ERLX1962A and AS4/976, were measured during thermal cycling between -200°F and 200°F. Tubes of each material with symmetric-balanced, symmetric and asymmetric wall construction, about 70 mils thick and 2 inches in diameter were studied. All of the tubes exhibited measurable twist due to temperature change. The twisting is due to the difference in the radial positions of off-axis layers which resulted in a moment about the tube axis. Thermal shear strain typical of the tubes with asymmetric wall construction is shown in the first figure. The experimental results are in good agreement with a generalized plane strain elasticity analysis, with temperature dependent material properties, developed for the tubes.

All of the tubes exhibited thermal twist, as shown in the chart. Both the symmetric and the asymmetric tubes had about the same amount of twist. Even the tube with the symmetric-balanced wall twisted, although the magnitude of twist was very small compared to that of the other tube configurations.

**Significance:** Twisting of tube elements can have serious consequences if the tube is part of a high-precision structure. In long unbalanced tubes, when the temperature change is large, the rotation of one end relative to the other can be significant. Over a long service life, such as 30 years, thermal fatigue could be detrimental to the structure. Also, this thermal twisting could introduce torsional loads into a structure that was not designed for torsional loads. Symmetric balanced fiber layups will avoid such consequences.

**Future Plans:** Future research will investigate the stresses induced in the end fittings and joints by thermal twisting of the tubular element.

# EFFECT OF COMPOSITE TUBE WALL CONFIGURATION ON THERMALLY INDUCED TWIST

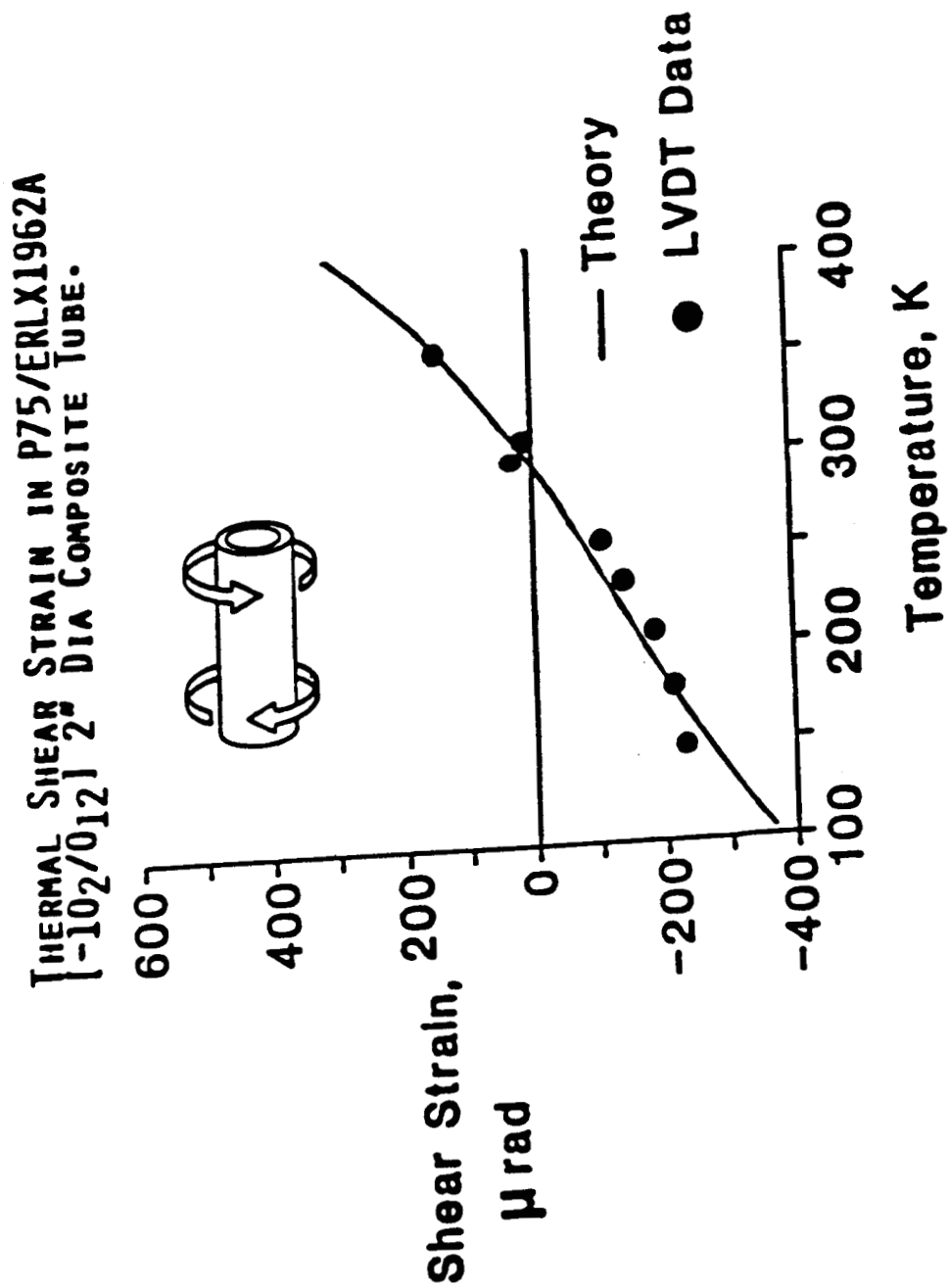


Figure 30(b).

# **EFFECT OF COMPOSITE TUBE WALL CONFIGURATION ON THERMALLY INDUCED TWIST**

<u>TUBE WALL LAYUP</u>		<u>TWIST IN 23' TUBE</u>	
		$\Delta T = -500^{\circ}F$	$\Delta T = -600^{\circ}F$
[10/05/-102/05/10] $\tau$	Symmetric balanced	0.005 deg.	0.006 deg.
[10/012/10] $\tau$	Symmetric unbalanced	10.2 deg.	12.3 deg.
[102/012] $\tau$	Asymmetric unbalanced	9.3 deg.	11.2 deg.

## THERMALLY STABLE GRAPHITE-REINFORCED ALUMINUM ALLOYS

Stephen S. Tompkins and Gregory A. Dries  
Applied Materials Branch  
Ext. 4558      December 1986  
RTOP 506-43-21

**Research Objective:** To develop continuous-fiber-reinforced aluminum-matrix composites that are thermally and mechanically stable over long times for dimensionally critical spacecraft.

**Approach:** Define high strength aluminum alloys that can be used as the matrix for P100/Al composites. Determine the thermal expansion behavior before and after long-time thermal cycling between -250°F and 250°F. Measure thermal expansion behavior using a laser interferometric dilatometer.

**Accomplishments:** Large residual strain and thermal strain hysteresis is typical of the thermal expansion behavior of P100/6061 composite shown in the first figure. This undesirable response has been significantly reduced, but not eliminated, by heat treatment. Heat treatment was not successful in increasing the yield strength of the alloy to the level needed to eliminate hysteresis. Significant loss of important alloy elements during fabrication was a key reason for lower than expected strengthening as seen in the second figure. Several high strength Al alloys were therefore investigated.

Combinations of commercial high strength aluminum alloy matrices and post-fabrication processes developed at Langley have resulted in metal-matrix composites that do not exhibit residual thermal strain or strain hysteresis during thermal cycling. The third figure shows the thermal expansion of composites composed of P100 graphite-reinforced 2024 and 201 Al alloy after 1000 thermal cycles between -250°F and 250°F. After post-fabrication processing, as well as after 1000 thermal cycles, neither composite exhibited residual strain or hysteresis.

**Significance:** A metal-matrix composite made with P100 and a high strength Al alloy such as 2024 or 201 provides a dimensionally stable Gr/Al composite for spacecraft that does not have the stability problems associated with moisture dryout, electron radiation, and atomic oxygen which are contributors to dimensional instability in polymer-matrix composites.

**Future Plans:** Future research will investigate thermal expansion behavior of Gr/Al angle-ply laminates using the high strength alloys. Analytical models of the thermal expansion of this class of material will be developed and verified.

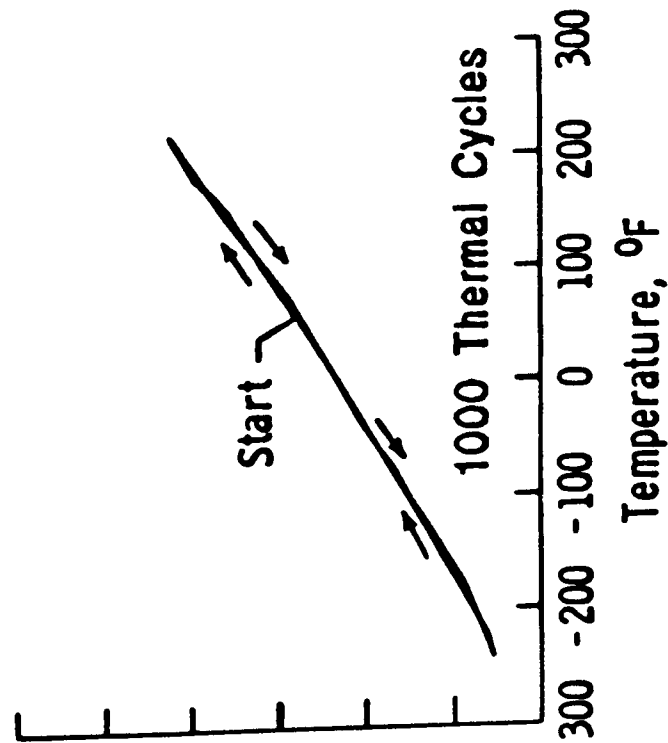
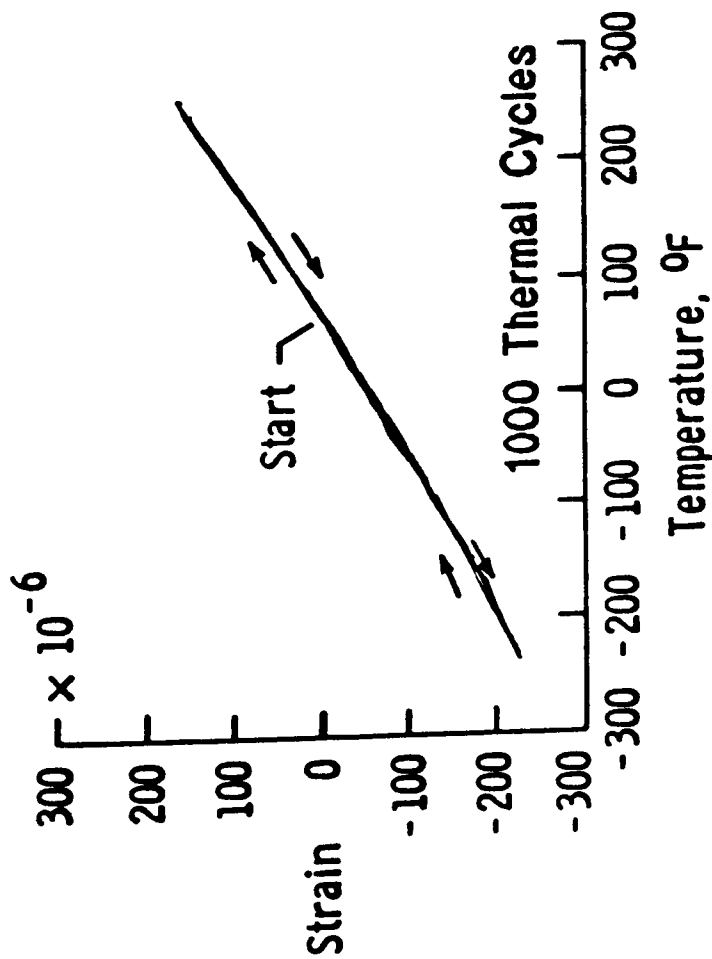
Figure 31(a).

# **THERMAL EXPANSION BEHAVIOR OF P100 Gr REINFORCED HIGH STRENGTH ALUMINUM COMPOSITES**

T6 Conditioned with Stress Relief at -268°F

P100 Gr/201 Al

P100 Gr/2024 Al



# A METHOD OF PREDICTING THE ENERGY-ABSORPTION CAPABILITY OF COMPOSITE SUBFLOOR BEAMS

Gary L. Farley  
Applied Materials Branch  
Ext. 2850 February 1987  
RTOP 505-63-01

**Research Objective:** To develop a simple and accurate method of predicting the energy-absorption capability of composite subfloor beam structure.

**Approach:** Develop a basic understanding of the crushing characteristics of composite materials. Determine the effects material and component geometry variables have on the energy-absorption capability of composite materials. Compare the crushing response of circular and square cross section tubes with structural elements.

**Accomplishment:** The subfloor beam structure of a helicopter must be designed to carry non-crash loads as well as to crush in a progressive manner to dissipate energy in a crash. Different types of stiffened and sine-wave beam concepts have been evaluated as shown in the first figure. Through a comprehensive study of the crushing characteristics of composite material, energy absorbing subfloor beam concepts have been developed that are superior energy absorbers to comparable metallic beams. However, the current method of designing energy absorbing composite beams is based upon a limited beam test data base because no means of predicting the energy-absorption capability exists.

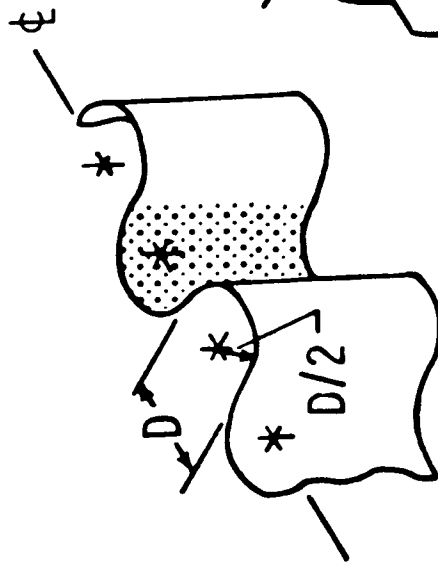
LaRC research results showed that the crushing modes of structural composite beams were similar to those of circular and square cross section tubes of similar composite material and fiber-reinforcement architecture. A hypothesis was formulated for predicting the energy-absorption capability of structural elements. The hypothesis is as follows: the crash energy-absorption capability of a structural element is the sum of the weighted average of the energy-absorption capability of its characteristic elements. Therefore, if the energy-absorption capabilities are known for composite tubes of different geometries, such as in the second figure, then the energy-absorption capability of a structural element can be predicted. Using this technique an energy-absorption capability of composite sine-wave and stiffened beams was predicted. Excellent agreement between prediction and experiment was obtained, as shown in the third figure.

**Significance:** The designer using the previously described prediction method can conduct design studies in a manner consistent with conventional structural design practice. This will reduce the cost of designing energy absorbing subfloor structure and will result in more efficient structure.

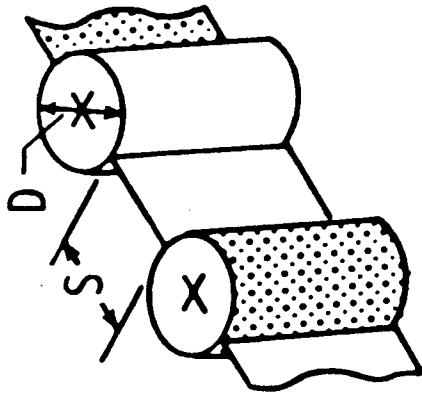
**Future Plans:** Future research will focus on the development of analytical procedures to predict the energy-absorption capability of composite tube specimens.

Figure 32(a).

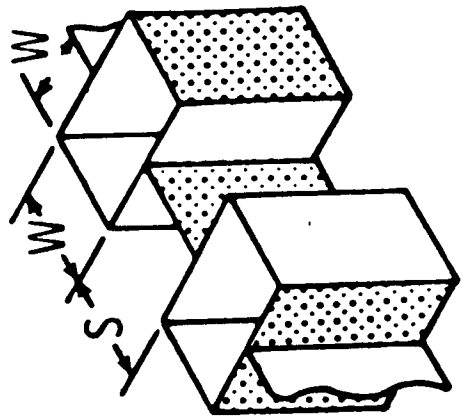
# ENERGY ABSORBING BEAM CONCEPTS



Sine-wave beam  
(tangent-half circle)



Circular tube  
stiffened beam



Rectangular tube  
stiffened beam



Figure 32(b).



# ENERGY ABSORPTION CAPABILITY OF SQUARE KELVAR/EPOXY TUBES

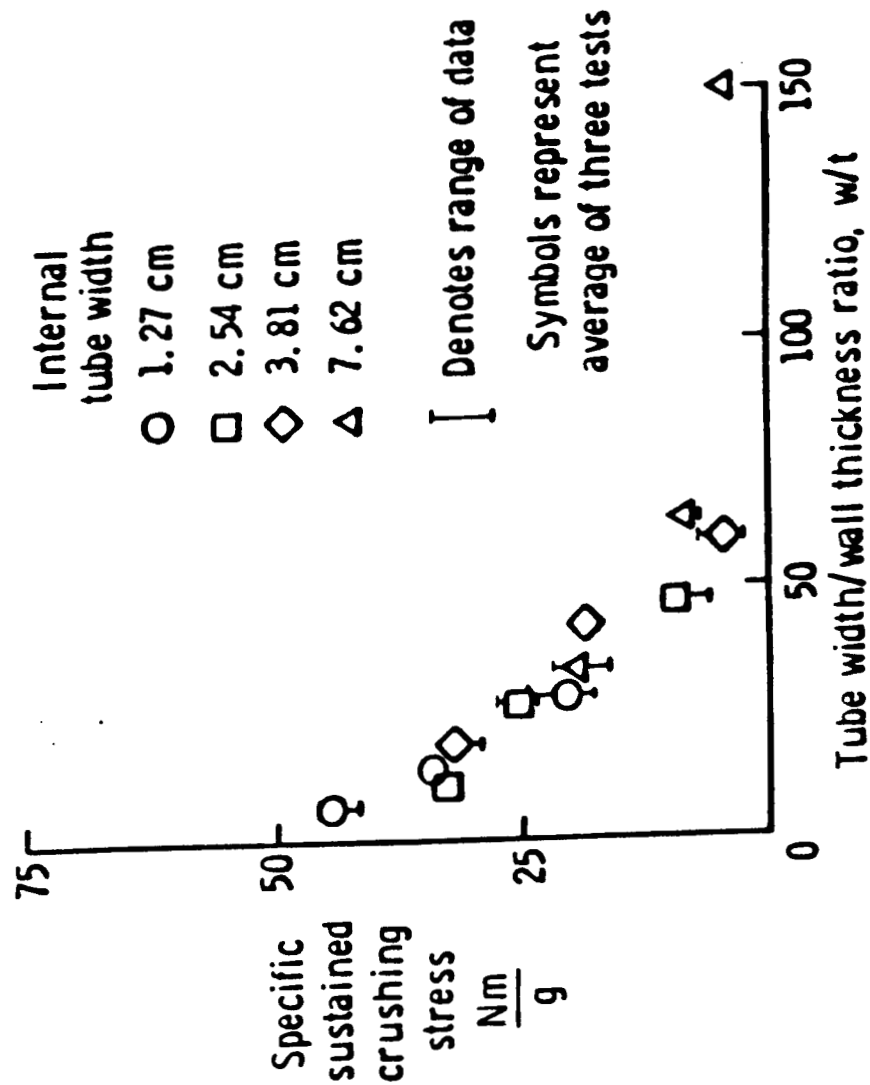
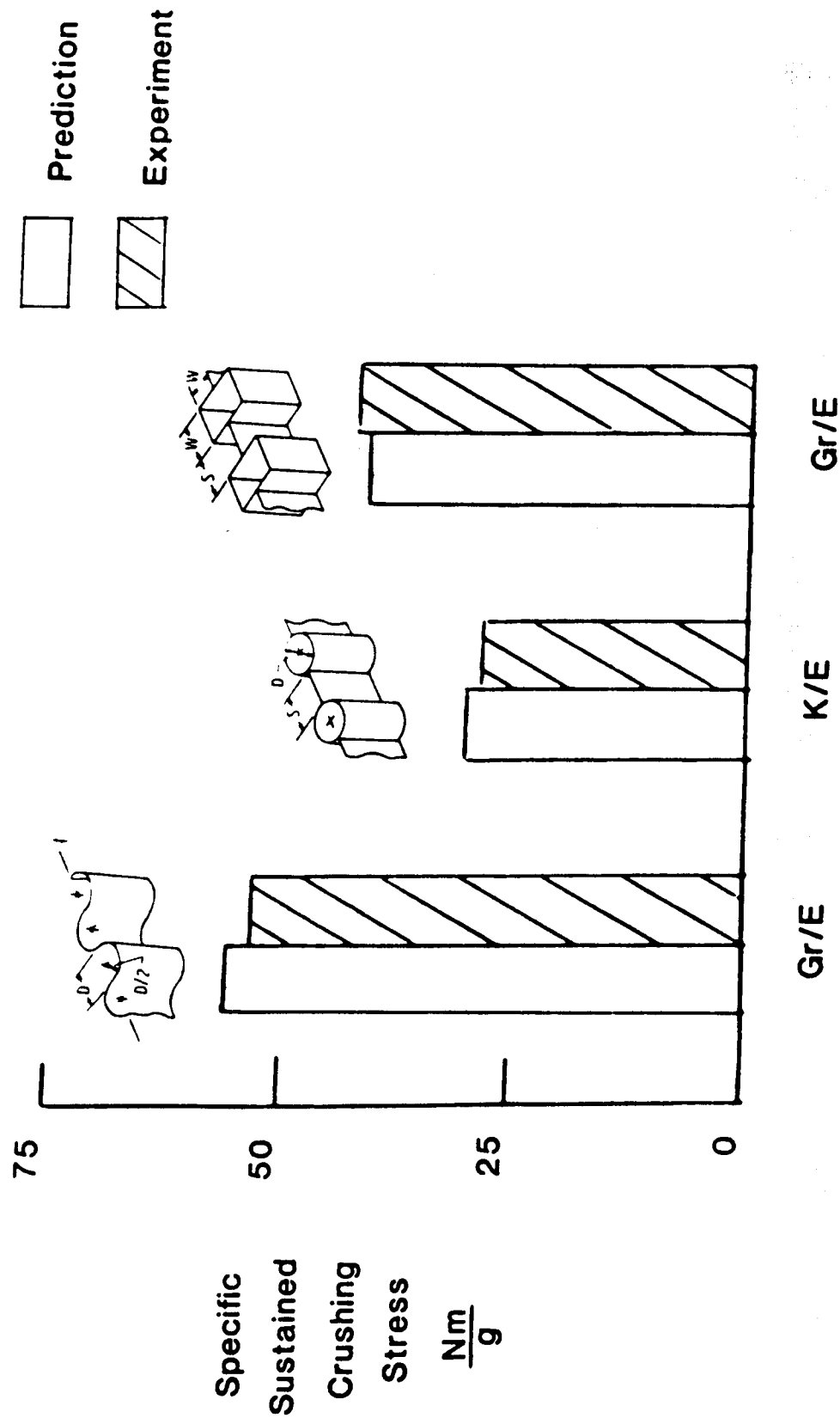


Figure 32(c).

# COMPARISON OF COMPOSITE ENERGY ABSORBING BEAMS PREDICTION WITH EXPERIMENT



This page intentionally left blank.

## USING FUNDAMENTAL SPECTROSCOPIC DATA TO EXPLAIN CHANGES IN APPLIED PROPERTIES OF IRRADIATED POLYMERS

Edward R. Long, Jr., and Sheila Ann T. Long  
Applied Materials Branch  
Ext. 3892 April 1987  
RTOP 506-43-21

**Research Objective:** To obtain a fundamental understanding of the changes caused by ionizing radiation on mechanical and electrical properties of advanced polymeric materials.

**Approach:** Polymer films are exposed to electron radiation for total doses up to the equivalent of 30 years exposure in geosynchronous orbit. The mechanical and electrical properties of irradiated specimens are compared to those of nonirradiated specimens to determine radiation durabilities. Spectroscopic analyses using electron paramagnetic resonance, infrared, and dielectric methods are used to determine changes in molecular structure caused by the irradiation. These combined analyses can explain which changes in the molecular structure caused the changes in the functional properties.

**Accomplishment:** Three generic polymeric systems have been studied: the polyetherimide Ultem, the polyimide Kapton, and the polyethylene terephthalate Mylar. Aromatic-structure-containing polymers such as these have been previously thought to be inherently radiation durable, but recent studies have shown that the durability depends on additional aspects of their molecular structures. For example, Ultem and Kapton contain the same aromatic structural components, but the effects of electron radiation on their total tensile elongations are different, as shown in the first figure. The additional molecular structure in Ultem, as shown in the second figure, is responsible for the difference. The radiation homolytically cleaves the aromatic ether bond in both polymers. The broken ether bond self-mends in Kapton. In Ultem, however, the radiation also causes hydrogen abstraction at nonaromatic sites. The abstracted hydrogen bonds to the phenyl radical at the site of the broken ether bond, thereby inhibiting self-mending. The polymer chains are thus free to crosslink, which is the cause of the large decrease in the elongation of Ultem. Similar studies have been made for the other mechanical and electrical properties of the three polymeric systems. The interpretations of the molecular data have led to consistent explanations of the radiation effects on those properties.

**Significance:** The identification of the molecular changes which cause the radiation-generated changes in the functional properties can suggest polymeric structures that are more radiation durable.

**Future Plans:** Similar studies on additional advanced polymers and studies on threshold and dose rate effects will be conducted.

# EFFECTS OF ELECTRON RADIATION ON TENSILE ELONGATION OF POLYMER FILMS

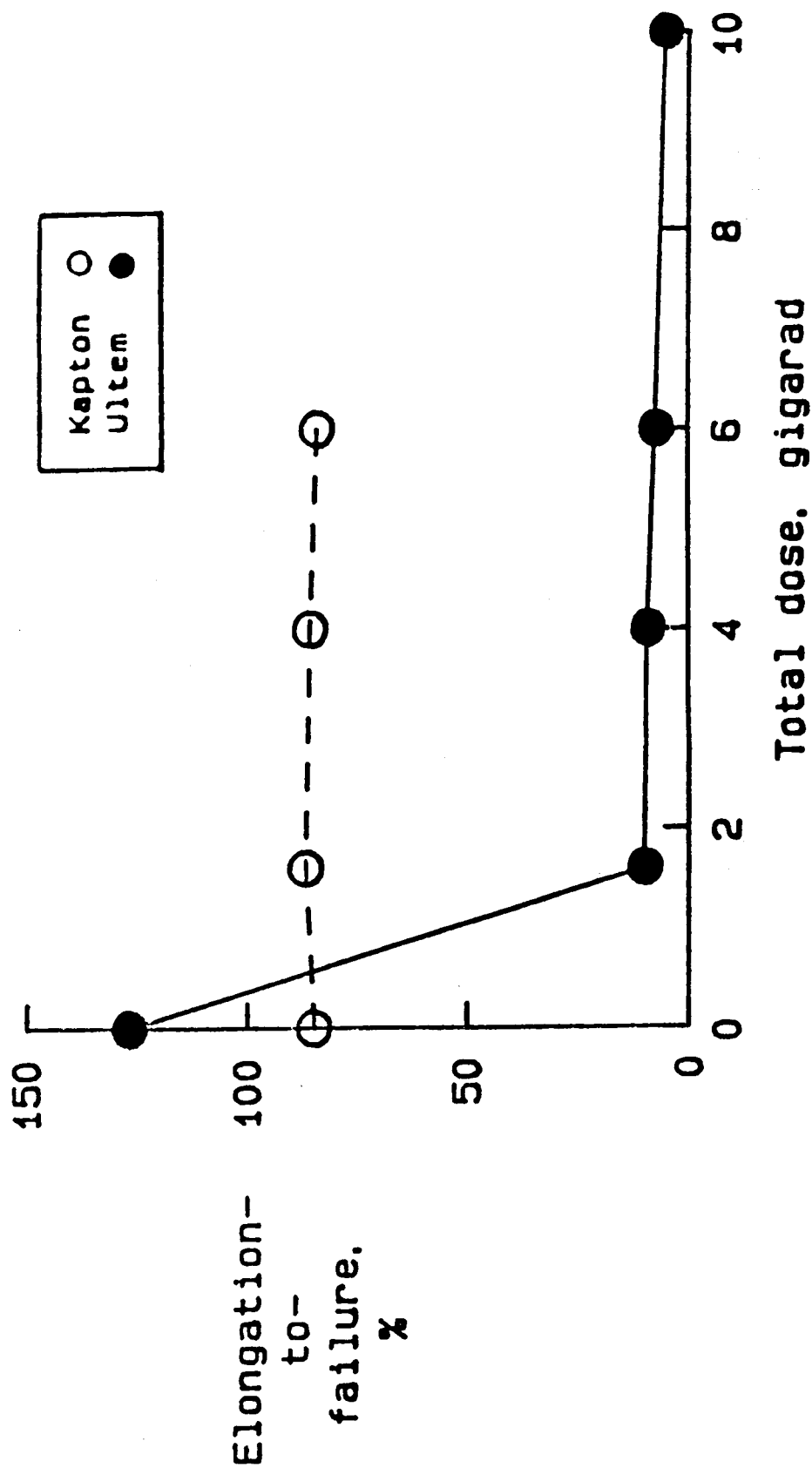
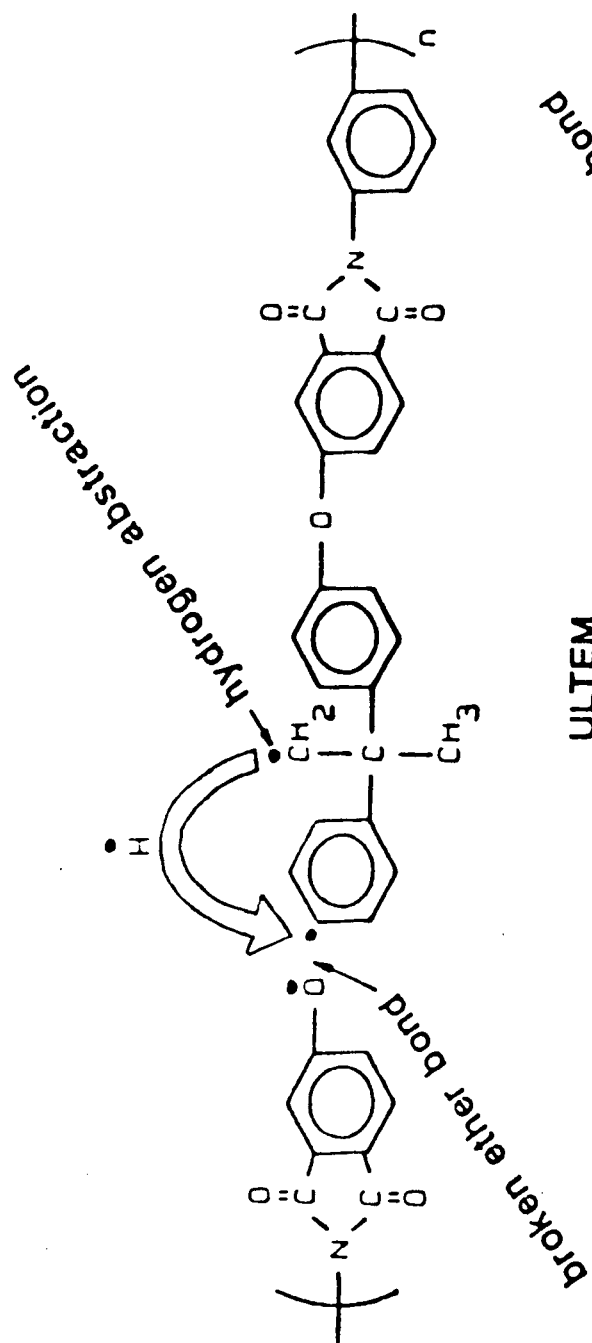
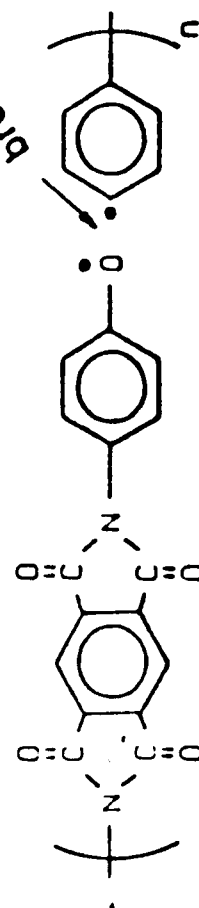


Figure 33(b).

# ELECTRON RADIATION EFFECTS ON MOLECULAR STRUCTURES



ULTEM



KAPTON

## INNOVATIVE FABRICATION OF COMPOSITE STRUCTURES

Marvin B. Dow  
Applied Materials Branch  
Ext. 2850 April 1987  
RTOP 505-63-01

**Research Objective:** To demonstrate the feasibility of pultrusion as an automated fabrication process for composite aircraft structures.

**Approach:** Develop tooling and techniques for pultruding stiffened panels incorporating damage tolerant design features. Pultrude a stiffened panel using thermoset-matrix composites and perform structural tests.

**Accomplishment:** The fabrication development is focused on pultruding graphite-epoxy plies to produce a stiffened panel of the dimensions shown in the first figure. The panel design incorporates structural efficiency and damage tolerance features such as "soft skin" and crack stoppers. These design requirements result in a complex arrangement of plies within the panel, shown in the second figure. Region 1 is the basic soft-skin layup with a high percentage of  $\pm 45^\circ$  plies. Region 2 are the "J" section stiffeners which feature  $0^\circ$  plies for strength. Region 3 are  $0^\circ$  crack stopper planks buried in the skin beneath the stiffeners. Region 4 are overlay plies which provide continuous attachments between stiffeners and the skin.

To provide the required design features and to accommodate the pultrusion process, dry AS4 graphite fabrics are slit to width, knitted as preplied elements, and wound on creels. Dry fabric from the creels is pulled through a pressurized tank which wets the fibers with Shell 9310 epoxy resin. From the wetting tank, the fabric elements are pulled through a curing die which shapes and cures the panel in a single operation. The panel is oven post-cured for 2 hours at  $350^\circ\text{F}$ .

A pultruded panel recently fabricated in this program is shown in the third figure. The fabrication was performed by Goldsworthy Engineering, Incorporated, under subcontract to Lockheed-California Company. The plan was to pultrude 30 feet of the stiffened panel, but an accumulation of problems forced a halt after 10 feet was pultruded. A 6-foot length of the panel has been delivered to Langley for testing.

**Significance:** One of the greatest challenges facing the aircraft industry is to reduce the acquisition costs for composite structures to a level below that of metal structures. The pultrusion process provides a means to automate the fabrication of composites and thereby reduce the costs. Results obtained in this investigation should help establish pultrusion as an acceptable process for fabricating the complex structures required in aircraft applications.

**Future Plans:** Other pultruded panels will be fabricated after improvements are made in the wetting tank and the pultrusion die. Structural tests will be performed to verify the structural quality of pultruded graphite-epoxy panels.

Figure 34(a).

# PULTRUDED PANEL DIMENSIONS

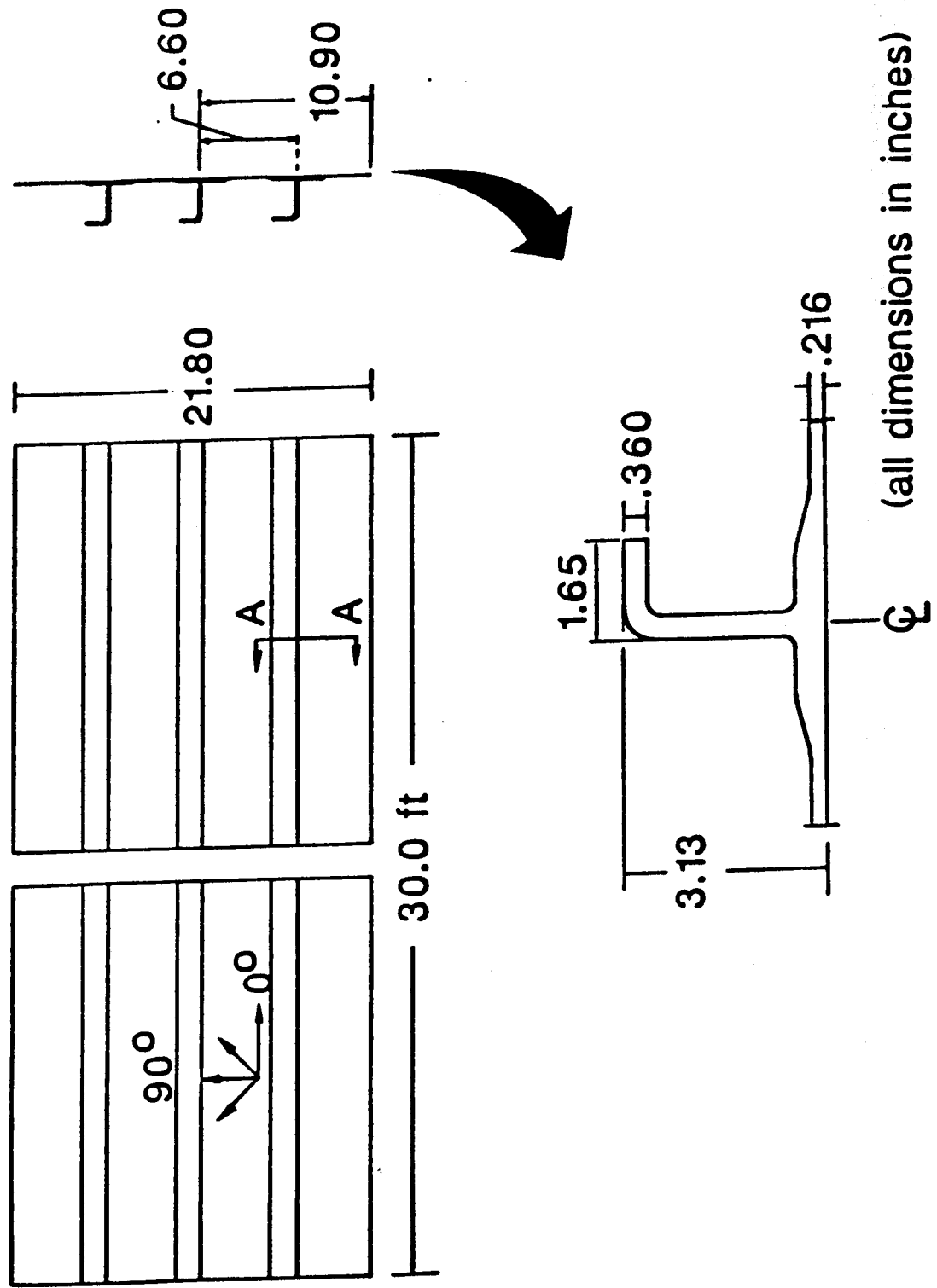


Figure 34(b).



# "J" PANEL STRUCTURE

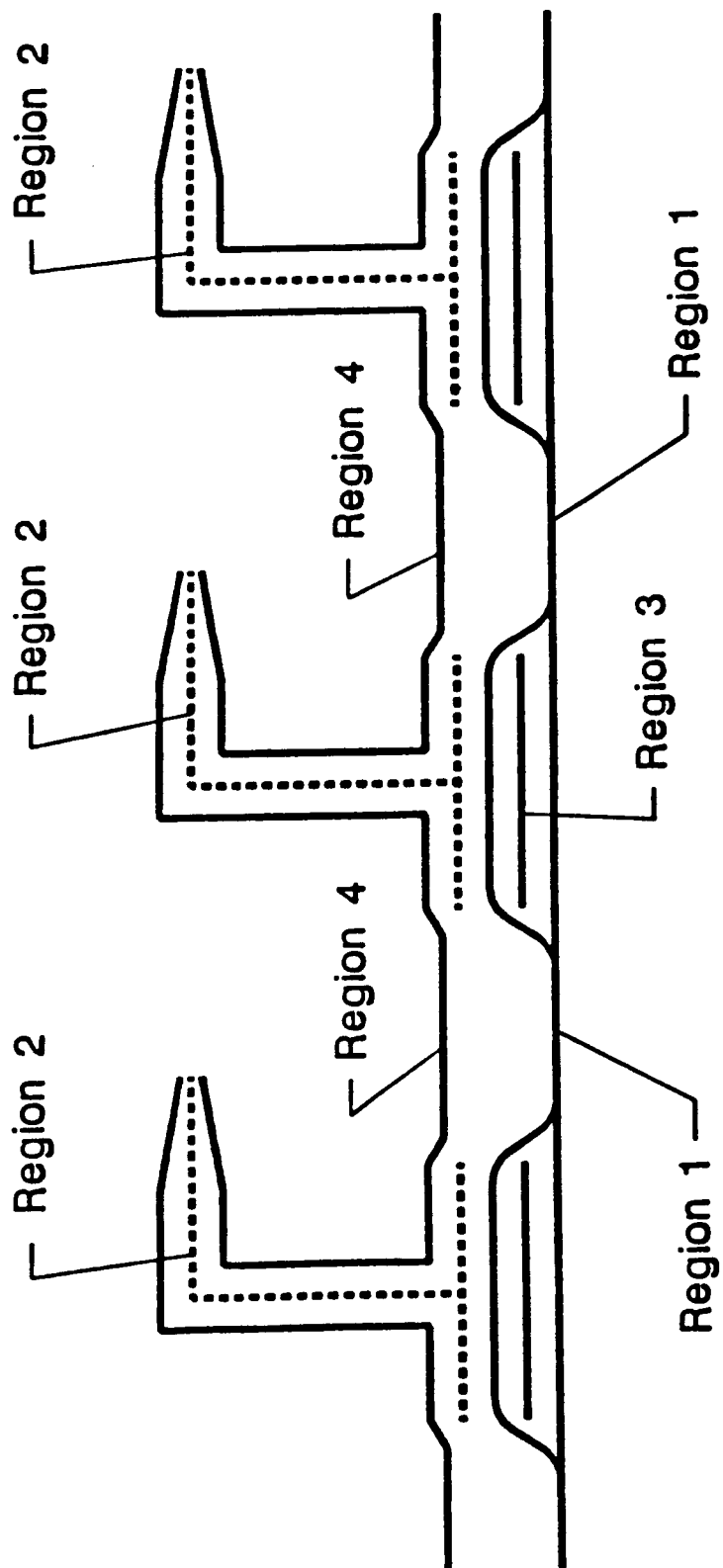


Figure 34(c).

# PULTRUDED COMPOSITE WING PANEL

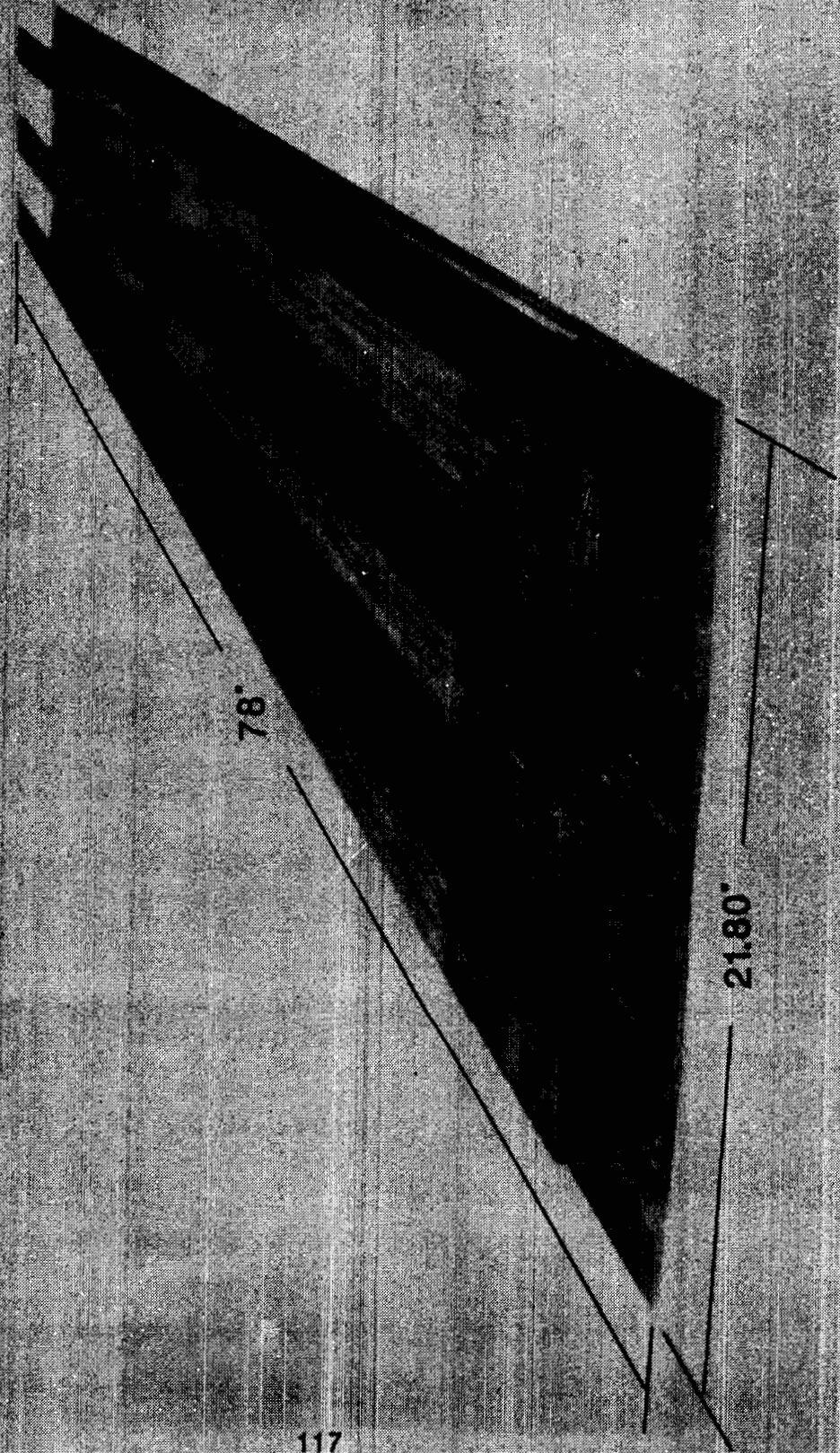
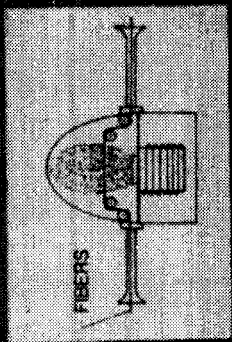
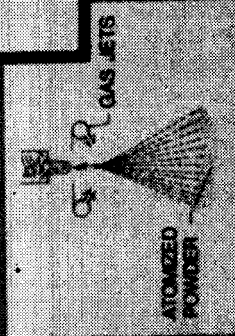


Figure 34(d).

# ALLOY SYNTHESIS

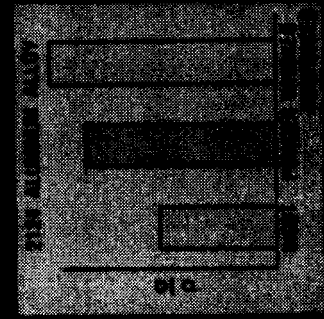


## PVD DEPOSITION

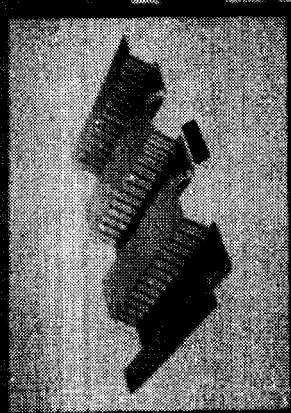


## PM RAPID SOLIDIFICATION

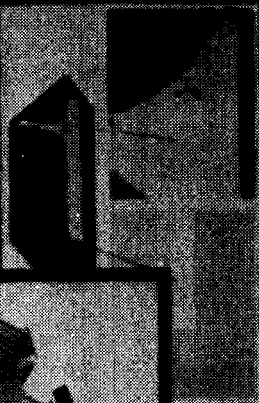
## MICROSTRUCTURE-PROPERTIES



# PROCESSING



## FORMING



## JOINING

## METALLIC MATERIALS

## EFFICIENT STRUCTURES

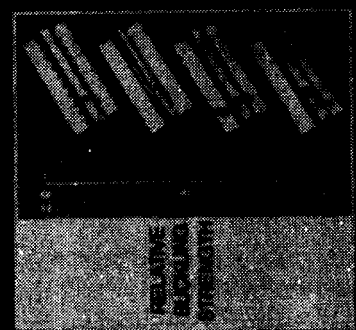


Figure 35

METALLIC MATERIALS BRANCH  
FIVE YEAR PLAN

MAJOR THRUST	FY87	FY88	FY89	FY90	FY91	EXPECTED RESULTS
Advanced light alloy and MMC development	PM aluminum alloys for high temperature and cryotanks					Improved metallics for transcentury and high speed transport aircraft
	Aluminum lithium alloy technology					
	Development & characterization of aluminum matrix composites					
	Secondary and thermomech. processing effects on metallurgical structure & mechanical properties of light alloys and MMC					
Innovative metals processing	Aluminum alloy modifications for enhanced superplasticity & diffusion bonding studies					Processing and joining methods for lighter weight, lower cost aerospace structures
	Suppression and control of cavitation and determination of SPF parameters for Al alloys					
High temperature thin gage metals and MMC for airframe applications	SPF/Al and Ti alloy material/structural integration studies					Higher specific strength and stiffness materials for hypersonic vehicle airframes
	High temperature brazing/diffusion bonding studies of foil gage Ti and AMMC					
	Synthesis and characterization of thin gage high temperature metal matrix composites					
	Properties and stability of intermetallic alloy substrates by deposition					

Figure 36.

# B4C PARTICULATES SHOW PROMISE TO IMPROVE PROPERTIES IN ALUMINUM MATRIX COMPOSITES

William D. Brewer  
Metallic Materials Branch  
Ext. 4193 January 1987  
RTOP 505-63-01

**Research Objective:** To develop 2XXX aluminum matrix composites with improved properties for high temperature aircraft structures applications.

**Approach:** Determine the effects of reinforcing phase, alloy chemistry, and primary and secondary processing on composite properties.

**Accomplishment:** Aluminum matrix materials reinforced with SiC whiskers have been shown to have properties that make them attractive for a variety of aircraft structural applications. At present, however, the whiskers are relatively expensive, about 15 percent more dense than aluminum, and have an aspect ratio sufficiently high (2:1 to 5:1 in final composite form) to result in composites with some anisotropy in properties. Boron carbide particulate reinforcement has the potential to overcome all of these shortcomings. The figure shows the strength, modulus, and strain to failure of 2124 Al/SiC and 2124 Al/B4C composite extrusions for different heat treatments and orientation (with respect to the extrusion direction). Heat treatment has little effect on either composite, whereas the orientation effects are obviously greater for the SiC whiskers than for the B4C particulates. In general, the properties of the two composites are about the same. However, the B4C is about 25 percent less dense than the SiC; and thus, for the same reinforcement volume fraction, the specific properties (density adjusted) of the B4C composite are somewhat better.

**Significance:** Because the B4C is less costly, less dense, and results in composites with properties at least as good as SiC whiskers, significant payoffs in terms of structural efficiency and cost may be realized by using the B4C reinforcements.

**Future Plans:** Composites processed with higher toughness alloys for the matrix and improved uniformity of distribution for the reinforcements investigated will be evaluated in terms of damage tolerance and durability.

Figure 37(a).

# MECHANICAL PROPERTIES OF 2124/SiC AND 2124/B<sub>4</sub>C COMPOSITE EXTRUSIONS

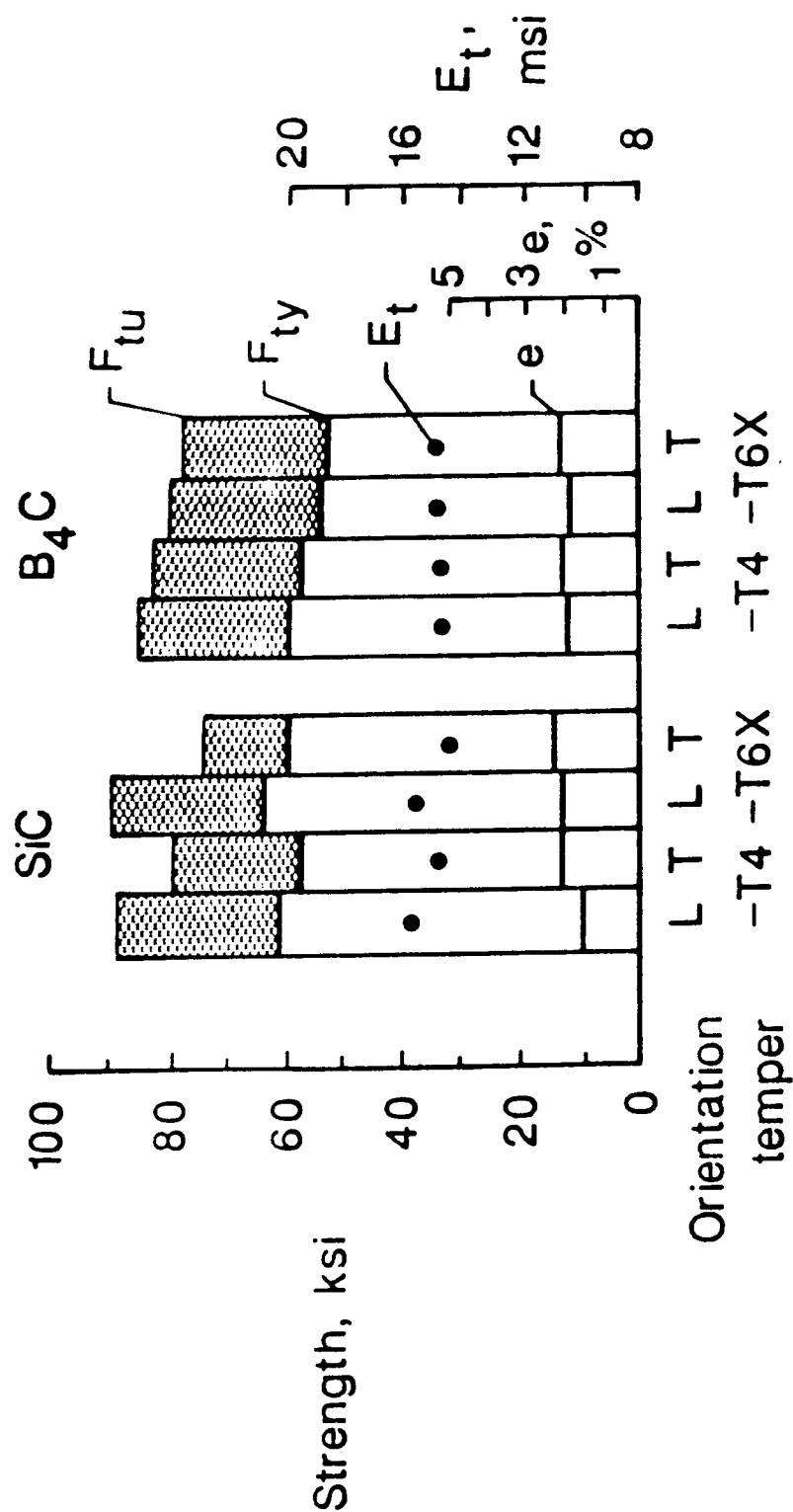


Figure 37(b).

## MATERIAL PROPERTY VERIFICATION OF LaRC PROCESSED PM ALUMINUM ALLOYS

O. R. Singleton  
PRC/Kentron, Inc.  
Ext. 2006 March 1987  
RTOP 505-63-01

**Research Objective:** To develop advanced aluminum alloys with improved strength and toughness properties for high temperature applications on high-speed civil transports.

**Approach:** Synthesize in-house research quantities of rapidly solidified, zirconium bearing PM Al alloy sheet using small consolidated billets prepared from powder supplied to LaRC from a CALAC-Alcoa contract. Compare material properties of LaRC produced sheet to those obtained from sheet produced from larger billets.

**Accomplishment:** In an initial phase, 31 billets of PM 2124+Zr aluminum alloy were produced from supplied powder, of which 27 were fabricated to sheet. Of these sheets, eleven contained the high 0.6% Zr used in the CALAC-Alcoa sheet material. Billet consolidation parameters of time, temperature, and vacuum were varied to achieve the desired material properties. As shown in the graph, the longitudinal and transverse tensile properties evaluated are nearly identical to those obtained on the contract study. These properties demonstrate that sheet material produced on a small laboratory scale can be utilized for advanced alloy synthesis studies.

**Significance:** A small in-house research facility will permit inexpensive and fast screening of innovative rapid solidification powder metallurgy aluminum alloy compositions. Rapid solidification appears to offer the most practical means to develop aluminum materials for use at temperatures of 600°F and above. Such aluminum alloys are not only lighter, but also potentially less expensive, than competing titanium alloys.

**Future Plans:** After completion of the material property sheet validation program, the methodology and equipment will be used to fabricate innovative P/M aluminum alloy sheet containing silicide additions. These aluminum alloys with potential for use at 600°F and above have densities under 2.9 g/cc. The research aluminum alloy powder has been purchased to specification through commercial suppliers.

Figure 38(a).

# MECHANICAL PROPERTIES OF ALCOA AND LaRC CONSOLIDATED ALUMINUM P/M 2124 + 0.6% Zr SHEET

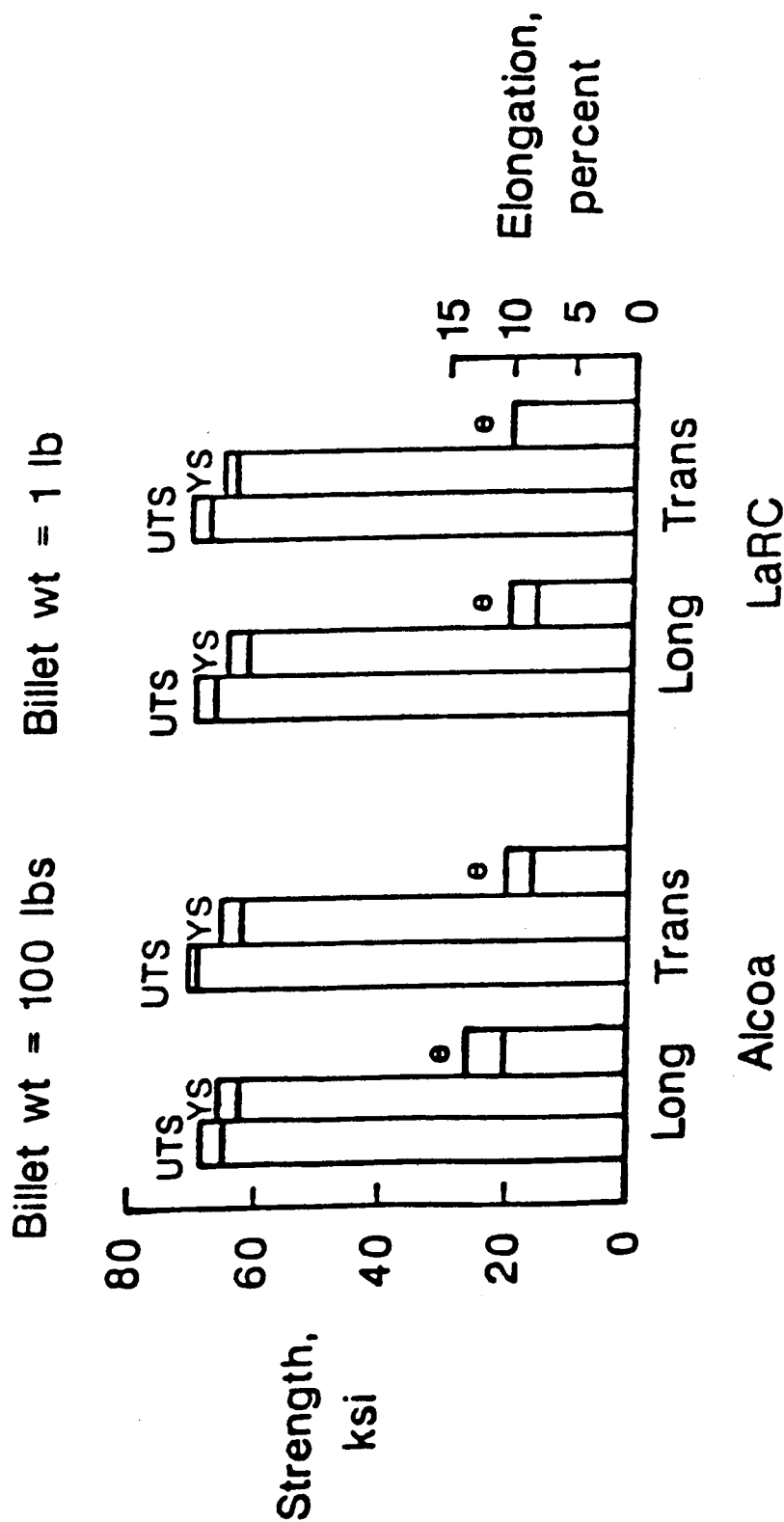


Figure 38(b).



## IMPROVED AGING CHARACTERISTICS BY MINOR ALLOYING ADDITIONS IN Al-Li ALLOYS

Linda B. Blackburn  
Metallic Materials Branch  
Ext. 4581 May 1987  
RTOP 505-63-01

**Research Objective:** To develop Al-Cu-Li-Zr-X alloys that can achieve high strength levels through direct heat treatment without requiring cold deformation prior to aging.

**Approach:** Add minor alloying additions of Cd, In, and Sn to a baseline alloy similar in composition to the 2090 Al-Li alloy, in an attempt to promote the precipitation of strengthening phases such as T<sub>1</sub> and m. Evaluate the effect of each addition on the aging response of each alloy at several aging temperatures. Determine the mechanical properties of peak-aged specimens and correlate microstructural features with the observed mechanical properties.

**Accomplishment:** Thermal analyses were conducted to identify optimum solution heat treatment temperatures in order to minimize the number of coarse constituent particles and maximize the amount of solute in solid solution. Aging response, as shown in the figure, indicates the In-bearing alloy resulted in significantly higher hardness than the other three alloys when aged at 160°C. Tensile tests conducted on specimens peak aged at 160°C also indicated the In-bearing alloy achieved the highest strengths. Charpy specimens tested in slow bend indicate the fracture toughness of the In-bearing alloy approaches that of baseline alloy and exceeds that of the Cd- and Sn-bearing alloys. TEM examination of the alloy microstructures indicates an increased density and homogeneity of the strengthening precipitates in the In-bearing alloy.

**Significance:** The ability to strengthen Al-Cu-Zr alloys through heat treatment alone makes it possible to consider forming the alloy in the solution treated condition before cold deformation or final aging. The material in this condition would have higher formability. The material should also be amenable to superplastic forming which would not be possible if cold deformation prior to aging were necessary.

**Future Plans:** The fracture toughness of each alloy will be more precisely determined and microstructural examinations will continue in order to determine the nature of the effect of minor alloying additions on the precipitation mechanisms of the strengthening phases. Mechanical property determination will be continued and sheet material will be prepared for conducting superplastic formability studies.

Figure 39(a).

# Al-2.3Cu-2.3Li-0.15Zr-X ALLOYS AGED AT 160°C

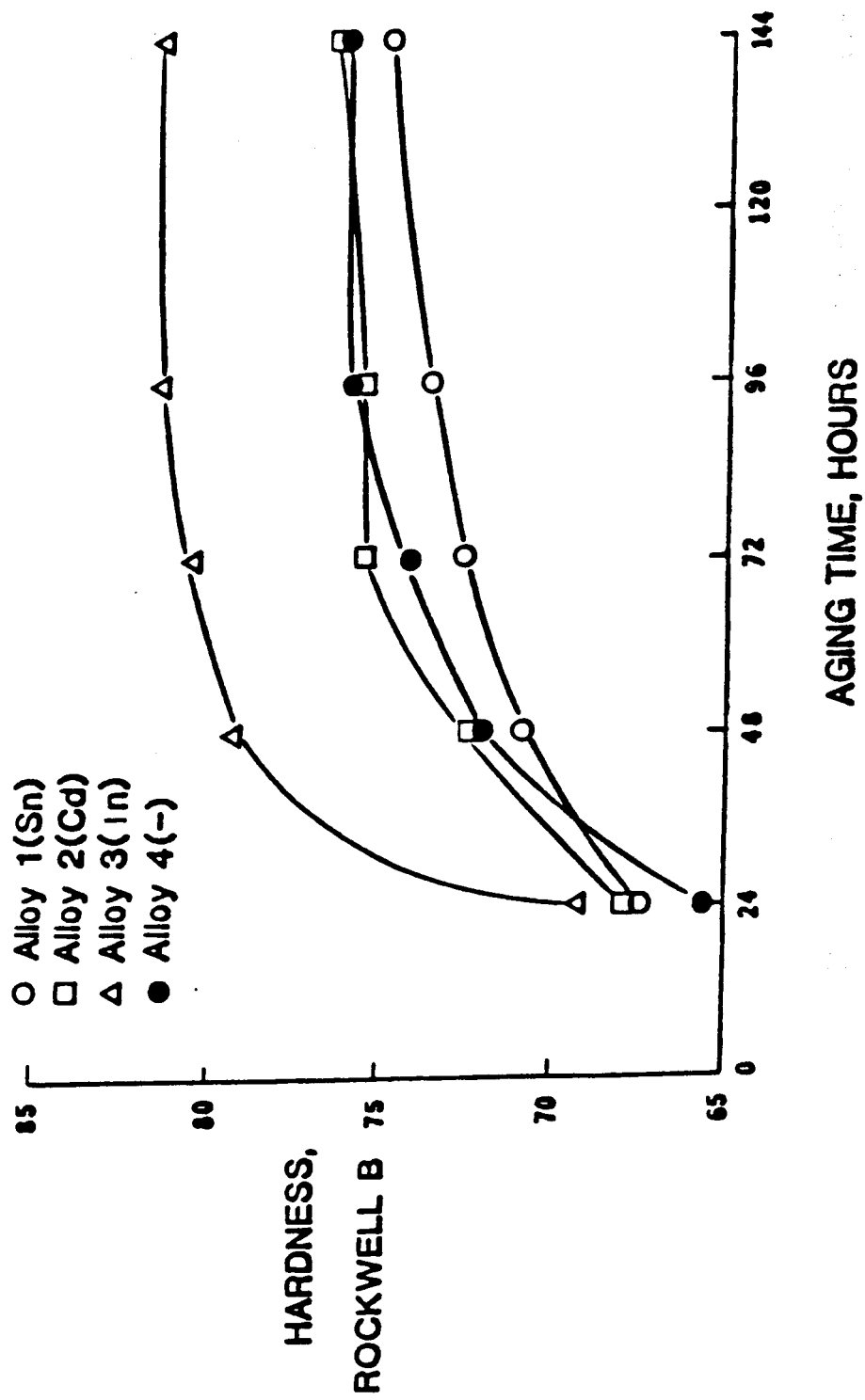


Figure 39(b)

# ALLEVIATION OF CAVITATION IN SUPERPLASTICALLY FORMED 7475 ALUMINUM ALLOY USING POST-FORMING PRESSURE

Thomas T. Bales  
Metallic Materials Branch  
Ext. 3405 November 1986  
RTOP 505-63-01

**Research Objective:** To develop the processing methodology to suppress cavitation in aluminum alloys resulting from the large strains associated with superplastic forming (SPF).

**Approach:** Conduct experimental studies to determine the feasibility of using post-forming pressure to heal cavitation resulting from SPF. Conduct metallographic analyses to determine the effect of various post-SPF pressures on the extent of void content.

**Accomplishment:** Superplasticity is the ability of selected metal alloys to undergo large strains (500-1000 percent) at elevated temperature prior to localized thinning or fracture. Processes have been developed for superplastically forming complex structural shapes in a single operation and result in significant cost savings compared to forming the same components using conventional means. When 7475 aluminum alloy sheet material is superplastically formed, internal porosity or cavitation is generated due to the metallurgical nature of the alloy. Methods to suppress or alleviate cavitation must be developed to realize the full potential offered by superplastic forming for reducing the cost of aerospace structural components. The figure shows the effects of post-forming pressure on cavitation. Specimens were superplastically formed at a temperature of 960°F using argon gas at a pressure of 100 psi. Following forming of the sheet material into the tool cavity, the post-forming gas pressure was increased and maintained for 1-1/2 hours. Several levels of post-forming pressure were investigated. Following exposure to the prescribed pressure-time profiles, metallurgical specimens were prepared and examined using a light microscope. A comparative image analyzer was used to determine the amount of porosity. As shown on the figure, the cavitation was reduced from approximately 2-1/2 percent for specimens subjected to a post-forming pressure of 125 psi to less than 1/4 percent for specimens exposed to 425 psi.

**Significance:** Results of this study indicate that post-forming pressure can be used to heal cavitation resulting from SPF. The technique is relatively simple and should extend the maximum forming strains for use in fabricating structural components.

**Future Plans:** Mechanical property tests are being conducted on specimens subjected to post-forming pressures to determine the effects of processing on material properties.

Figure 40(a).

# EFFECT OF POST-FORMING PRESSURE ON CAVITATION OF 7475 ALUMINUM ALLOY

960°F, 1-1/2 hours

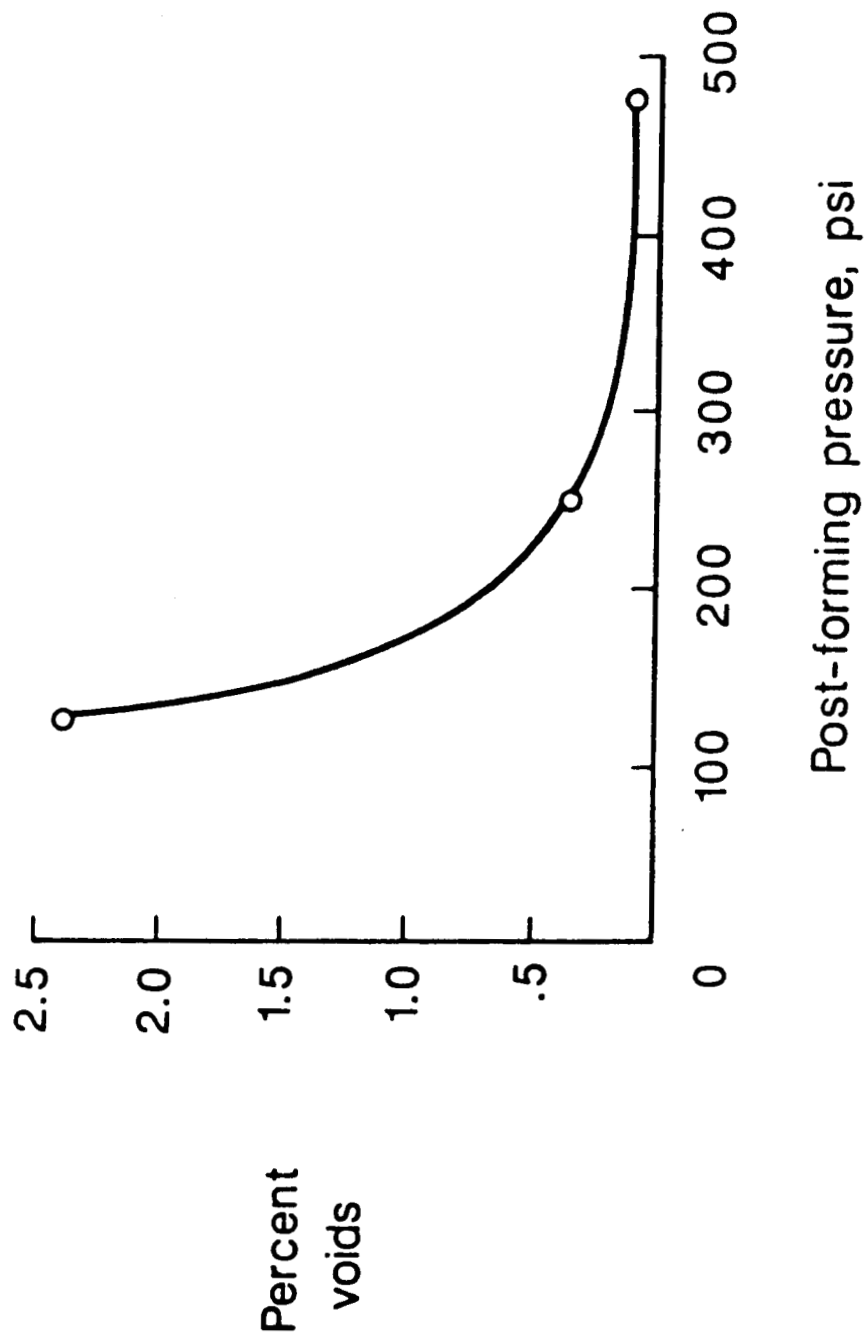


Figure 40(b).

## EMITTANCE/CATALYSIS COATINGS TO IMPROVE PERFORMANCE OF TITANIUM-ALUMINIDES

Ronald K. Clark and Teryl A Wallace  
Metallic Materials Branch  
Ext 4557 July 1987  
RTOP 506-43-71

**Research Objective:** To develop high emittance-low catalysis-oxidation resistant coatings for advanced high temperature structural metallic materials.

**Approach:** Candidate coatings are selected/formulated to reduce catalysis and increase emittance. Current focus is on titanium-aluminide based material systems prepared with coatings using sputtering, physical vapor deposition, chemical vapor deposition, and slurry processes. Coated specimens are screened for emittance-oxidation performance. Promising candidate coatings are subjected to preliminary reentry simulation testing for 1 hour which includes about four 4 thermal cycles. The catalysis of specimens is evaluated from the temperature rise rate of the specimens on exposure to the test environment. Coatings that meet performance requirements for the research objective are tested for 5 hours. Post test analysis of coatings include spectral reflectance measurements and metallurgical examination including x-ray diffraction and scanning electron microscopy.

**Accomplishment:** A single titanium-aluminide alloy with three different coatings has been subjected to preliminary reentry simulation testing for 1 hour at a surface temperature of 1800°F. As shown on the figure, all three coatings reduced catalytic heating by 30 percent and increased the emittance to a favorable level (> 8).

**Significance:** Minimum structural weight of NASP structures requires coatings that lower the vehicle surface temperature by re-radiation of energy (high emittance) and by reducing the catalytic heating resulting from gaseous recombination (low catalysis). Coating must also provide oxidation protection of the substrate materials which are susceptible to oxidation.

**Future Plans:** Post exposure specimens will be subjected to metallurgical analysis including SEM, XRD, and microprobe of the specimen surface and cross-section. Results of this evaluation will be input to NASP contractors for possible use in coating modification activities. Most outstanding candidate coatings will be tested for 5 hours at 1800°F in the LaRC HYMETs facility.

Figure 41(a).

# EMITTANCE/CATALYSIS COATINGS IMPROVE PERFORMANCE OF TITANIUM-ALUMINIDE

Ti-14Al-19Nb-8Mo

Before reentry test      After reentry test

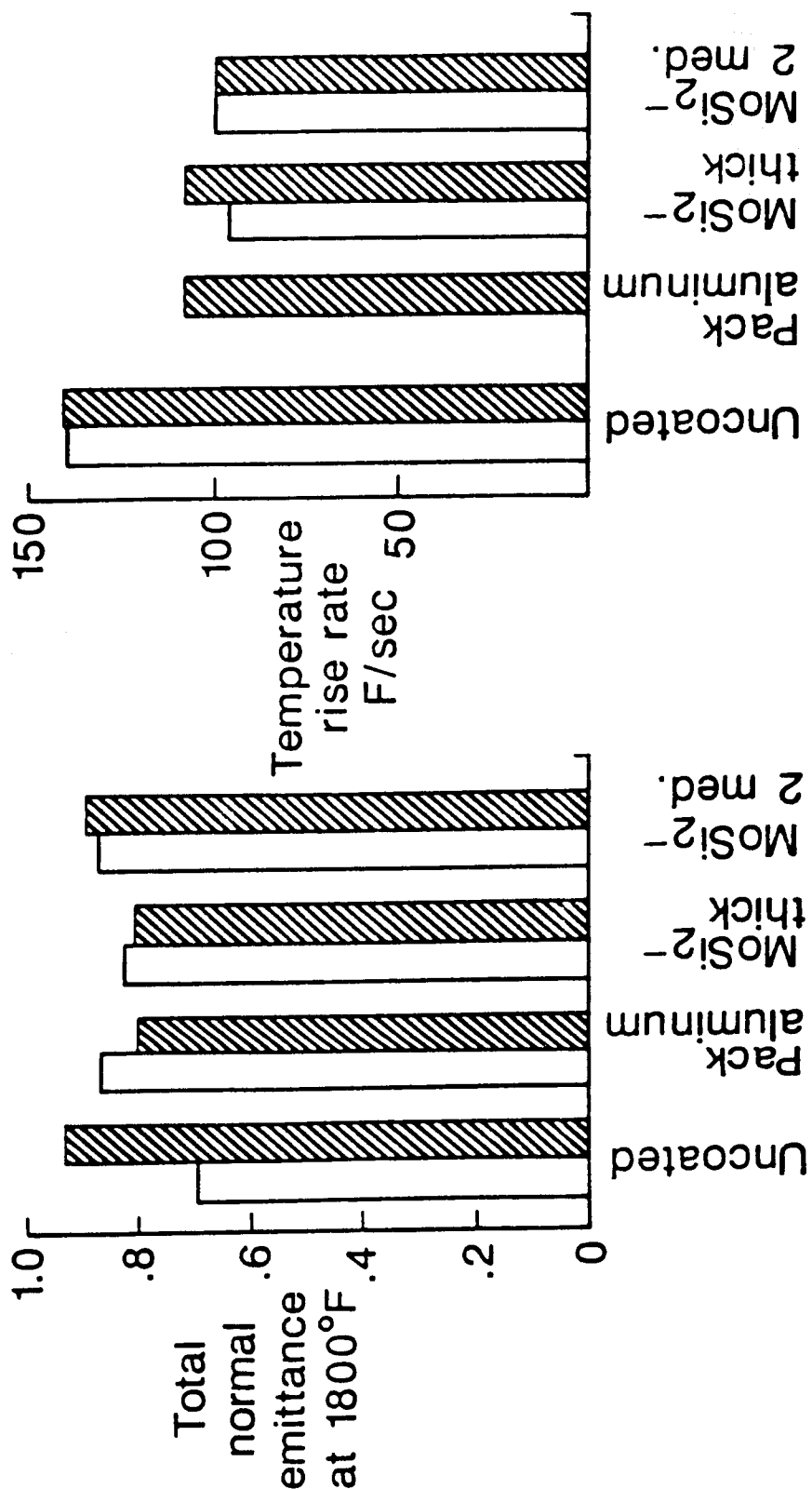


Figure 41(b).

# LIQUID INTERFACE DIFFUSION BONDING OF TITANIUM ALUMINIDES SHOWS PROMISE FOR ELEVATED TEMPERATURE APPLICATIONS TO 1700°F

R. Keith Bird and Eric K. Hoffman  
Metallic Materials Branch  
Ext. 2212 September 1987  
RTOP 763-01-41

**Research Objective:** To develop advanced joining processes for fabricating Ti<sub>3</sub>Al metal-matrix composite and RSR titanium honeycomb-core sandwich structure and demonstrate upper use temperatures through testing and analysis.

**Approach:** Conduct in-house studies using ingot metallurgy (IM) titanium aluminide model materials to develop joining processes suitable for fabricating Ti<sub>3</sub>Al composite sandwich structure. Utilize candidate liquid interface diffusion (LID) bonding materials and parameters to produce simple Ti<sub>3</sub>Al - Ti<sub>3</sub>Al butt joints. Optimize process parameters to achieve highest joint strength with minimum added weight. Measure joint strength over a range of elevated temperatures and determine the factors controlling the strength achieved. Analytical techniques include energy dispersive x-ray analysis and microprobe analysis for the determination of the composition of the material at the joint and scanning electron microscopy to determine the microstructural effects of the LID bonding process on the parent metal.

**Accomplishment:** Ti<sub>3</sub>Al butt joints were fabricated using two different LID bonding material compositions. The joints were evaluated at elevated temperatures up to 1700°F. The figure shows the joint strength results. At the higher test temperatures the pure copper LID bonding material exhibits higher joint strengths than the copper/silver mixture. The LID bonding processes examined to date show promise for application at elevated temperatures, but further optimization is required.

**Significance:** Minimum structural weight of NASP structures requires the use of honeycomb-core sandwich panels with thin-gage Ti<sub>3</sub>Al face sheets. The core/face sheet joint must exhibit adequate mechanical properties in the temperature regimes of interest. In addition, the joining process must result in minimum added weight to the structure.

**Future Plans:** Additional LID bonding material compositions will be utilized to fabricate Ti<sub>3</sub>Al butt joints for elevated temperature evaluation. The optimum LID processes will be used to produce honeycomb-core sandwich panels with Ti<sub>3</sub>Al face sheets. These panels will be subjected to mechanical property evaluation at elevated temperatures.

**Figure 42(a).**

# LID BONDED $Ti_3Al$ BUTT JOINT STRENGTH VS. TEMPERATURE

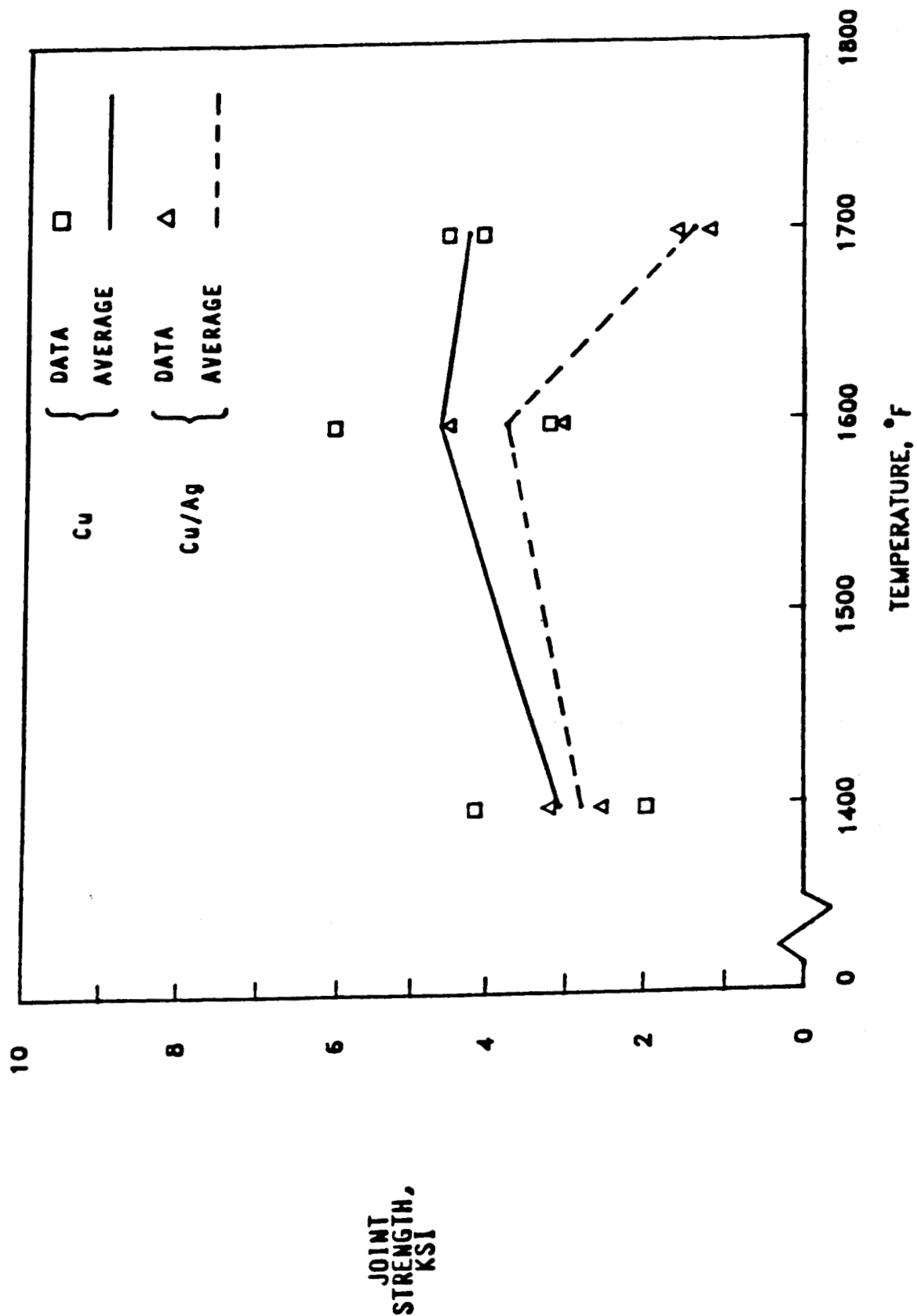


Figure 42(b).

JOINT  
STRENGTH,  
KSI



## POLYMERIC MATERIALS BRANCH

### FY 88 PLANS

- o Synthesis of improved polymers
  - Thermoplastics (homo and copolymers)
  - Thermosets
  - Blends and IPNs
  - Low CTE
- o Expand composite work
  - Resin scale-up
  - Better quality prepreg (powder coating)
  - Optimize composite fabrication processes
  - Innovative fabrication techniques
- o Structure/property relationships
  - Polymer synthesis (CTE, modulus, etc.)
  - Composite constituent relationships
  - Fiber-matrix interface
  - Adhesives

Figure 43.

## FATIGUE AND FRACTURE BRANCH

### FY 88 PLANS

- o Metals and MMC
  - Continue short crack cooperative programs
  - Begin to address crack growth in cryotankage alloys
  - Start elevated temperature fatigue and fracture testing SiC/Ti<sub>x</sub>Al MMC
- o Composites
  - Develop viscoelastic micromechanics analysis
  - Emphasize fatigue of tough composites
  - Begin fatigue and fracture analysis of multidirectional composites
- o Computational methods
  - Continue development of multi-grid method
  - Continue cooperative effort with computational structural mechanics group
- o Shuttle support
  - Complete O-ring testing

## APPLIED MATERIALS BRANCH

### FY 88 PLANS

- o Space materials
  - Verify durability of Space Station tube materials and thermal control coatings
  - Develop advanced composites for precision segmented reflectors
- o High temperature composites
  - Assess lifetime of SOA carbon-carbon composites in NASP mission environments
  - Develop sealants for refurbishment/repair of carbon-carbon coatings
  - Initiate development of in-house CVI/CVD capability
- o Composites for aircraft/rotorcraft
  - Develop multidirectional, multilayer weaving technology for net shape panels
  - Develop resin transfer molding and pultrusion concepts for woven/braided preforms

Figure 45.

## **METALLIC MATERIALS BRANCH**

### **FY 88 PLANS**

- o Advanced aluminum alloy technology
  - PM alloys for higher temperature airframe applications
  - PM and aluminum-lithium alloys for cryogenic tank applications
- o Processing and joining
  - Fabrication, testing, and evaluation of curved cap compression panel
  - Explore SPF feasibility for cryogenic tank application
- o High temperature  $\text{Ti}_x\text{Al}$  and AMMC metallics for hypersonics and NASP
  - Continue growth of in-house processing and characterization
  - New emphasis on high temperature thin gage metal matrix composites
  - Development of deposition techniques for thin gage MMC



## Report Documentation Page

1. Report No.  NASA TM-101506	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle  Materials Division Research and Technical Accomplishments for FY 87 and Plans for FY 88		5. Report Date  December 1988	
		6. Performing Organization Code	
7. Author(s)  Kay L. Brinkley		8. Performing Organization Report No.	
		10. Work Unit No.  506-43-11-02	
9. Performing Organization Name and Address  NASA Langley Research Center Hampton, Virginia 23655-5225		11. Contract or Grant No.	
		13. Type of Report and Period Covered  Technical Memorandum	
12. Sponsoring Agency Name and Address  National Aeronautics and Space Administration Washington, DC 20546-0001		14. Sponsoring Agency Code	
15. Supplementary Notes			
16. Abstract  The research program of the Materials Division is presented as FY 87 accomplishments and FY 88 plans. The accomplishments for each Branch are highlighted and plans are outlined. Publications of the Division are included by Branch. This material will be useful in program coordination with other government organizations, universities, and industry in areas of mutual interest.			
17. Key Words (Suggested by Author(s))  Materials Research Plans Accomplishments Objectives		18. Distribution Statement  Unclassified - Unlimited  Subject Category - 23	
19. Security Classif. (of this report)  Unclassified	20. Security Classif. (of this page)  Unclassified	21. No. of pages  136	22. Price  A07